

Nils Bulling

Formal Methods for Analysing, Coordinating, and Controlling Decisions in Multi-Agent Systems

Habilitation Thesis (cumulative)

Contents

Preface	VII
1 Introduction	1
2 Reasoning about Strategic Aspects in Decision Making	5
2.1 Logics for Reasoning About Strategic Abilities in Multi-Player Games	8
2.2 Comparing Variants of Strategic Ability	8
2.3 Agents With Truly Perfect Recall	12
2.4 Combining Quantitative and Qualitative Reasoning	15
2.5 Alternating-Time Epistemic μ -Calculus	17
2.6 Taming the Complexity of Linear Time BDI Logics	19
3 Coordination and Control of Multi-Agent Decision Making	23
3.1 Verifying Normative Behavior via Normative Mechanism Design	24
3.2 Monitoring Norm Violations in Multi-Agent Systems	26
3.3 Coalitional Responsibility in Strategic Settings	28
4 Analysing Multi-Agent Decision Making	31
4.1 A Survey of Multi-Agent Decision Making	33
4.2 A Game-Theoretic Approach to Stability in Mobile Ad-Hoc Networks	34
4.3 Reaching Your Goals Without Spilling The Beans: Boolean Secrecy Games	36
4.4 A Boolean Game Based Modelling of Socio-Technical Systems	37
5 Conclusions	41
References	43
A List of Publications Contributing to the Thesis	49

Preface

“Four years have passed since the beginning of my PhD studies in Clausthal.” This is the first line of my PhD thesis and I can say almost the same now: another four years have passed since the beginning of my “habilitation project”—in retrospect to the time of submission. I received my PhD in October 2010; thereafter, I was employed as an assistant professor in the Computational Intelligence group, led by Prof. Dr. Jürgen Dix, at Clausthal University of Technology for another four years. Today, however, it is safe to say that there won’t be yet “another four years” in Clausthal: a vacancy at TU Delft in the Netherlands arose where I have started as an assistant professor in the Interactive Intelligence group in February 2015.

Before my move abroad early this year, I took the final steps towards the completion of my habilitation in Computer Science. On the 9th of December 2014, I gave the scientific talk¹ on *Suchalgorithmen* (search algorithms), followed by the *Probevorlesung* on *Grundlagen der Computersicherheit* (foundations of computer security) on the 7th of January 2015. My habilitation thesis itself is *cumulative*, consisting of 13 papers and the present extended summary of my work. My thesis continues, to some extent, the line of research of my PhD, and, to a greater one, investigates formal methods to analyze, control and coordinate the decision making of agents in multi-agent systems. The reviewer committee consisted of: Prof. Dr. Jürgen Dix (TU Clausthal), Prof. Dr. Thomas Eiter (TU Vienna), Prof. Dr. Jörg Müller (TU Clausthal), Prof. Dr. Michael Wooldridge (University of Oxford). I feel very honoured that they were part of my habilitation process and am very grateful for their effort.

Finally, I am particularly thankful to Jürgen Dix for the great time in his group and his continuous support. I have learnt a lot from him and have always very much enjoyed working for him and with him. I hope that we will stay in touch.

Delft, October 13, 2015

Nils Bulling

¹ The habilitation process requires to give two talks: the *Wissenschaftlicher Vortrag* and the *Probevorlesung*.

Introduction

We have been accustomed to computer systems that do what we tell them to do—provided that they do not malfunction. Calculators do the arithmetic we ask them to; word processors take keyboard inputs, process and display them; databases store the data entered by users. From this perspective, computers are electronic slaves. Indeed, these examples are not very astounding: today’s computer systems are more intelligent. If a customer buys a product at Amazon, the customer will automatically get suggestions for future shoppings, which are often quite adequate; as if Amazon knew ones desires. Of course, this is no magic but “just” a clever algorithm which makes recommendations based on existing (historical) data. We have become used to such recommender systems [Resnick and Varian, 1997; Adomavicius and Tuzhilin, 2005], and have higher demands on computer systems. A computer system/program should support us on a daily basis; it should behave intelligently and pro-actively (i.e. doing something without explicitly being asked about), function in a goal-driven way, and be reliable. Since the 90s programs with such characteristics are often referred to as (*intelligent*) *agents* [Wooldridge and Jennings, 1995]. It is easy to imagine many of these agents operating in the same environment, working together or against each other, pursuing their own tasks or a common task. A key feature of *multi-agent systems* (MASs) [Wooldridge, 2013, 2009; Ferber, 1999; Wooldridge and Jennings, 1995] is autonomy: agents take their decisions autonomously, possibly selfishly in order to achieve their objectives. If objectives of agents are aligned or if help of others is required, cooperation and interaction with other agents can be beneficial, or even necessary, to solve their complex tasks. In order to be successful in cooperating and interacting with others, agents need to be skilled in many disciplines, e.g. they need to be able to communicate [Chopra and Singh, 2013], cooperate, and negotiate [Kraus, 1997], as well as to reason strategically. All that requires agents to make good decisions.

The following example illustrates this. In a smart household it is easy to imagine a variety of tasks to be performed by intelligent agents. An agent hovers the floor, others regulate the temperature, or order groceries. Agents can also be used to optimize the day schedule of the home owner, of course taking recent events like the weather forecast into account. To take the burden from the customer, each agent should pursue its tasks in a completely autonomous manner, no need to instruct the hover robot when it is time to start the cleaning. Although all agents pursue their own tasks, they need to communicate and cooperate with each other. The scheduler agent, for example, should make sure that noisy tasks are performed when the house owner is away and assign robots to the available recharging stations. This requires robots to plan and to negotiate with each other, possibly making compromises one way or another.

This example illustrates that there are situations in which the behaviour of the agents needs to be coordinated in order to achieve a satisfactory overall behaviour emerging from the agents individual activities. Coordination can be sufficient if agents' objectives are aligned. If this is not the case, however, more sophisticated mechanisms are needed. Many reasons can require the coordination of agents' behaviour in order to avoid undesirable effects like deadlocks. The desired system behavior of the MAS can be a combination of the agents individual tasks or any other property specified by the system designer/ the system principal. Still, it is important to emphasize that agents are primarily interested in satisfying their own objectives. As a consequence, the *emergent system behavior* may not satisfy the system specification: control mechanisms are needed. This is a challenging task and not as simple as it may look, due to the agents' autonomy. In this context, control often means trying to convince agents to act in specific ways, e.g. by providing incentives which give agents a reason to follow a course of action that is desirable for ensuring the system objective. To offer the right incentives and to design appropriate mechanisms, this requires to understand agents' behavior and their decision making process.

In our example of a smart home, norms can, e.g., be used to prohibit hovering at night hours. Enforcing this norm can be achieved by the regimentation of violating behavior, thereby intervening in the agent's autonomy. Alternatively, sanctions can be imposed to deal with norm violations, not directly affecting the agent's autonomy. For example, if the hover robot performs its task at night hours, the scheduler could sanction the robot by assigning it less time for recharging. It is up to the hover robot to comply with the norm or to bear the consequences. An regimenting approach could simply ensure that the robot is switched off at night.

Smart grids provide another timely example of MASs in which decisions and behaviors need to be coordinate and controlled. Smart grids describe future power grids; first (prototypical) small-scale smart grids have already been developed and are being tested. A smart grid involves different stakeholders each of which with its own interests and objectives. Power suppliers, e.g., want to maximize profit, but also have to ensure good power quality (avoiding energy peaks, blackouts, etc.) and have to comply with regulations. On one hand, users want to minimize costs, but also expect constant and reliable power availability, as well as transparent and personalized tariffs; on the other hand, they want their privacy to be ensured. Thus, optimization is possible along different dimensions which usually required to make trade-offs. A further challenge is the use of renewable energy which may not guarantee a flat power output. This requires a good prediction of the behavior of users. Based on these models, methods with the aim to change the habits of users' can be developed. For example, users could be disincentivized to use machines with a high electricity demand at peak hours. This illustrates the importance of a careful *analysis* and *prediction* of user behavior in order to design customized tariffs and to have accurate estimations of the expected power usage. Similarly, the activities of electricity producers, which can be customers or the power providers themselves, need to be *coordinated*. More power needs to be provided at peak hours, whereas it can be necessary to downscale power production at other times. Simple coordination may be insufficient in cases of emergency situations, e.g. to prevent acute blackouts; intelligent control mechanisms need to come into operation.

Another challenge of the settings described above is their high complexity, resulting, e.g., from the various interactions taking place between the different actors. To cope with this complexity tools to model, analyse, verify and simulate such systems are needed. In this thesis we investigate foundational principles of such tools for analysis, controlling and coordinating complex interactions and decision making in MASs. The contributions of this thesis can be divided into three parts which focus on:

1. formal methods for specifying and reasoning about the decision making of agents, focussing on strategic aspects. We consider different (strategic) logics to capture characteristics of agents' capabilities affecting their decision making. This is the subject of Chapter 2.
2. formal methods to coordinate and to control agents' decisions. We investigate rules and norms to incentivize agents to change their way of acting such that the emerging system behavior complies with the system specification. Aspects of detecting norm violations and ascribing responsibility to agents are discussed. This is the content of Chapter 3.
3. how game theoretical methods can be used to analyze, predict, and understand how intelligent agents take their decisions. These methods can serve as foundation of smart applications; we present one such approach showing how to compute stable/fair network topologies in mobile ad-hoc networks using game theoretical methods. This is the topic of Chapter 4.

Reasoning about Strategic Aspects in Decision Making

In the late 90s, Alur et al. [1997, 2002] proposed the *alternating-time temporal logic* (ATL) ATL^* and its syntactically restricted fragment ATL . The logics merge temporal logic with basic game theoretic concepts and allow to reason about strategic abilities of groups of agents. This can be thought of a game between two opposed groups of players trying to bring about a property and to prevent it, respectively. Here, bringing about means that the proponents have a winning strategy—a strategy that is successful against all the opponents’ counter-strategies. The property can be a temporal or strategic property; for example, it can specify that the scheduler robot and the hover robot of our smart home example working together as a team can guarantee that the hovering task is performed during the day, independent of the actions of all other robots. The language of ATL^* is given by formulae φ generated by the grammar:

$$\begin{aligned}\varphi &::= \mathbf{p} \mid \neg\varphi \mid \varphi \wedge \varphi \mid \langle\langle A \rangle\rangle\gamma \text{ with} \\ \gamma &::= \varphi \mid \neg\gamma \mid \gamma \wedge \gamma \mid \mathbf{X}\gamma \mid \mathbf{G}\gamma \mid \gamma\mathbf{U}\gamma\end{aligned}$$

where $\mathbf{p} \in \mathcal{I}$ is a proposition drawn from the set of all propositions \mathcal{I} , and A is a set of agents drawn from the set of all agents Agt . The logic ATL restricts¹ ATL^* by requiring that each temporal operator, \mathbf{X} (in the next moment), \mathbf{G} (always from now on) and \mathbf{U} (until), is immediately preceded by a cooperation modality $\langle\langle \cdot \rangle\rangle$. For example, $\langle\langle A \rangle\rangle\mathbf{X}(\varphi\mathbf{U}\psi)$ is an ATL^* -formula but not an ATL -formula. We usually denote agents by natural numbers $1, 2, \dots$ and variables referring to them by a, b, \dots . The temporal operator $\mathbf{F}\gamma \equiv \top\mathbf{U}\gamma$ (now or sometime in the future γ holds) is defined as macro. The formula $\langle\langle 1 \rangle\rangle\mathbf{X}\langle\langle 2 \rangle\rangle\mathbf{F}\text{win}$ expresses² that agent 1 has a strategy to ensure that in the next moment agent 2 has a strategy to achieve eventually win. Goranko and van Drimmelen [2006] proposed a sound and complete axiomatization of ATL that allows to reason about strategic abilities of agents.

Concurrent game structures (CGSS) serve as models³ of ATL^* . These are transition systems/Kripke structures in which transitions are labelled by joint action profiles, consisting of one action per agent, enabling the very transitions. An example of a CGS is shown in Figure 2.1. States are represented by q_i for $i = 0, 1, 2$. An action tuple has the form $(\text{push}, \text{wait})$ containing an action of the first agent (*push*) and of the second agent (*wait*). As common for Kripke structures, states are labelled with propositions representing the information available at them; in the figure, proposition pos_0 is true at state q_0 . A *path* λ in a model is an infinite sequence of states (an

¹ In the case of ATL^* the temporal operator \mathbf{G} (now and always) can be defined as macro $\mathbf{G}\gamma \equiv \neg\mathbf{F}\neg\gamma$.

² For “small” coalitions like $\{1, 2\}$ we just write $\langle\langle 1, 2 \rangle\rangle$ instead of $\langle\langle \{1, 2\} \rangle\rangle$.

³ Other models have been proposed as well, e.g. alternating transitions systems and modular interpreted systems.

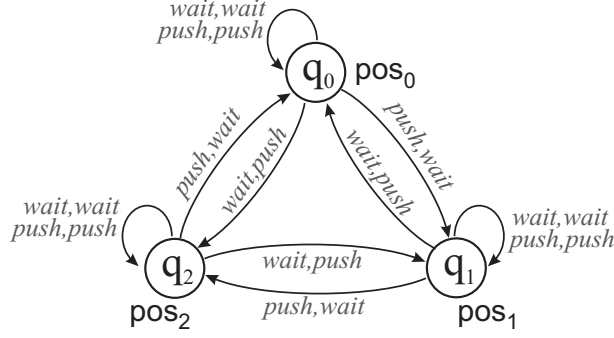


Fig. 2.1. Two robots and a carriage: concurrent game structure \mathfrak{M}_0

element from Q^ω) interconnected by transitions, e.g. $q_0q_1q_2^\omega$ is a path in the model \mathfrak{M}_0 . The path models the system behavior in which the systems starts in q_0 , then transitions to q_1 and then changes its state to q_2 in which the system remains forever. Analogously, a *history* is a non-empty, finite sequence of interconnected states (an element from Q^+). We use $\lambda[i]$ and $\lambda[i, \infty]$ to refer to the i th state on λ and to the subpath starting at position i , respectively.

Crucial is the notion of *strategy*. It is a conditional plan that describes (or prescribes) what the agent is going to do. A *perfect recall, perfect information strategy for an agent a* (also called *IR-strategy*⁴) is defined as a function $s : Q^+ \rightarrow \text{Act}$ mapping state sequences to actions such that, if $s(q_1 \dots q_n) = \alpha$ then action α is available to agent a at state q_n . Given a model \mathfrak{M} , a state q in the model and a collective strategy s_A —i.e. a set of strategies consisting of one strategy for each agent in A —the *outcome* of s_A from q in \mathfrak{M} is the set of all paths that are consistent with s_A , semi-formally:

$$\begin{aligned} \text{out}_{\mathfrak{M}}(q, s_A) = \\ \{ \lambda \mid \lambda \text{ is a path starting in } q \text{ resulting from agents in } A \text{ following their strategy } s_A \} \end{aligned} \quad (2.1)$$

It is important to note that agents outside A , i.e. $\text{Agt} \setminus A$, can act arbitrarily. Hence, in general the outcome set contains more than one path. The formal semantics of formula $\langle\langle A \rangle\rangle \varphi$ is defined as follows:

$\mathfrak{M}, q \models_{IR} \langle\langle A \rangle\rangle \varphi$ if, and only if, group $A \subseteq \text{Agt}$ has a collective *IR*-strategy s_A (i.e. a collection of individual strategies, one per agent from A) such that for all paths $\lambda \in \text{out}_{\mathfrak{M}}(q, s_A)$ we have that $\mathfrak{M}, \lambda \models_{IR} \varphi$.

As already mentioned above, the subscript *IR* indicates that agents are assumed to have perfect information about the world (*I*) and perfect recall (*R*). For illustration we consider Figure 2.1. We have that $\mathfrak{M}_0, q_0 \models_{IR} \neg \langle\langle 1 \rangle\rangle \mathbf{F} \text{pos}_1$ expressing that it is not the case that agent 1 can ensure to eventually make pos_1 true. Formally, this means that for all *IR*-strategies s_1 of player 1 there is a path $\lambda \in \text{out}_{\mathfrak{M}_0}(q_0, s_1)$ in the outcome set of the strategy, such that there is no natural number i with $\mathfrak{M}_0, \lambda[i, \infty] \models \text{pos}_1$. A “winning” strategy of 1 does not exist, because agent 2 is not a member of the proponent coalition $\{1\}$, and 2 can prevent agent 1 from reaching state q_1 by performing the *push* action in q_0 and the *wait* action in state q_2 . But we have that $\mathfrak{M}_0, q_0 \models_{IR} \langle\langle \{1, 2\} \rangle\rangle \mathbf{F} \text{pos}_1$: together, agents 1 and 2 have the ability to eventually guarantee to make pos_1 true.

⁴ We shall use *I* (resp. *i*) to refer to perfect (resp. imperfect) information. Analogously, we use *R* and *r* in the context of memory.

Often, agents have only incomplete information about the world. To model this, CGSSs are extended by *indistinguishability relations* between states, one per agent. Such a relation $\sim_a \subseteq Q \times Q$ for an agent a captures that two states in relation cannot be distinguished by agent a . CGSSs in the context of incomplete information are called *incomplete information concurrent game structures* (ICGSSs). Incomplete information also affects the notion of strategy. Not all strategies are *executable* anymore. Intuitively, an agent must assign the same choice to indistinguishable histories—there would be no justification if the agent chose different actions at situations which appear identical to it. Such strategies are called *uniform*; formally, if histories h and h' (i.e. finite sequences of interconnected states) cannot be distinguished by a , written as $h \approx_a h'$, then the actions a strategy s_a assigns to h and h' must be identical, i.e. $s_a(h) = s_a(h')$.

As mentioned above, logics such as ATL* can be used to specify properties of open systems. For example, in the context of security it can be expressed that the security controller is able to ensure that access is only granted to privileged users. The semantics of the logic captures the capabilities of the agents, here of the security controller. Therefore, it is crucial that the capabilities are captured accurately. It must be defined what the agents know about the model and what computational power the agents have. For example, it can make a difference if the security controller can only use a simple state based strategy to secure the system, or a more complex strategy that takes into account all past events.

In this section we investigate formalisms that capture the different assumptions underlying the agents' decision making. Formally speaking, the different semantics yield possibly different *logics*⁵ which in turn capture general properties of games. In Section 2.2 we investigate the precise relation between different strategic logics. In Section 2.3 we argue that the standard ATL* semantics can yield counterintuitive behaviors: agents forget past events even under the assumption of perfect recall. We propose a new semantics and analyze its properties.

So far, the discussed logics are purely qualitative. They can express that some state of affairs is reached or that all states satisfy a given property. These logics do not allow to reason about quantitative aspects. Though, these aspects are inherent to many real-world settings and are also crucial in the decision making of agents. Examples of systems which usually have a quantitative dimension are resource bounded systems and systems in which actors have monetary objectives. Objectives in smart grids, for example, can require to specify the actual power consumption, or users monetary costs. In Section 2.4 we propose a quantitative extension of ATL*. As a consequence, agents are no longer restricted to purely qualitative objectives. They can have objectives such as $\langle\langle 1 \rangle\rangle \mathbf{G}(\text{travel} \wedge v_1 \geq 100)$ expressing that agent 1 can always travel and at the same time has at least 100 Euro. The logic can also be used in combination with resource-bounded systems or in settings in which agents take costs into consideration.

In Section 2.5 we propose an epistemic extension of the *alternating μ -calculus*, proposed by Alur et al. [2002]. Our extension is appealing because it provides a new notion of strategy *and* has—for a restricted setting—better computational properties than corresponding variants of ATL* in the incomplete information setting.

Logics can essentially serve two main purposes: system modeling/specification/verification, and reasoning. In both cases computational complexity [Papadimitriou, 1994] issues are crucial for the logics applicability, perhaps even more if agents use logics for reasoning as they have to (re)act in a timely manner. In Section 2.6 we identify (fragments of) logics for reasoning about agents' mental states that have good computational properties.

In the following sections we summarize the work of this section in more detail.

⁵ In this context, a logic is considered to be the set of all tautologies/valid sentences over a given language together with a semantics and a class of models (semantic approach), or given a language and an axiomatic system (syntactic approach) [Blackburn et al., 2001a].

2.1 Logics for Reasoning About Strategic Abilities in Multi-Player Games

This section summarizes:

Bulling, N., Goranko, V., and Jamroga, W. (2015). Logics for Reasoning About Strategic Abilities in Multi-Player Games. In van Benthem, J., Ghosh, S., and Verbrugge, R., editors, *Models of Strategic Reasoning*, number 8972 in LNCS, pages 93–136. Springer

In this article we discuss formal methods for reasoning about strategic ability in multi-player games. We review strategic games and effectivity functions which are abstract models of strategic power of coalitions. An *effectivity function* $E : 2^{\text{Ag}t} \rightarrow 2^{2^{\text{Out}}}$ assigns to a set A of agents a set of sets of states, each of which encodes a set of outcomes group A is effective for. That is, if $X \in E(A)$ this means that agents A can *ensure* the outcome to be in X . In the paper we discuss how effectivity functions and strategic games are related [Pauly, 2001a; Goranko et al., 2013]. Then, we proceed with concurrent game models and relate them to global effectivity models. We introduce Coalition Logic [Pauly, 2001a,b] and ATL^* [Alur et al., 1997, 1998, 2002]. Both logics allow to model and to reason about strategic abilities of agents in one-step and multiple-step games. Coalition logic is equivalent to the next-time fragment of ATL . We give an overview of variants of ATL^* , for example ones in which agents are committed to their strategies, or where strategic terms are part of the object language allowing to explicitly talk about specific strategies. Thereafter, we survey logics to reason about games—in the game theoretical sense—and to characterize game theoretical solution concepts. We also consider incomplete information settings and present the most prominent epistemic extensions of ATL^* . We conclude reviewing results on satisfiability and model checking of ATL^* . The contribution of this article is a survey on strategic reasoning, focussing on ATL^* and its variants.

2.2 Comparing Variants of Strategic Ability

This section summarizes:

Bulling, N. and Jamroga, W. (2014). Comparing variants of strategic ability: how uncertainty and memory influence general properties of games. *Journal of Autonomous Agents and Multi-Agent Systems*, 28(3):474–518

2.2.1 Strategies and Semantic Variants

The standard variants of ATL , as defined in [Alur et al., 1997, 2002], are based on *perfect information* and *perfect recall*. This is reflected in the way strategies are defined, as functions $Q^+ \rightarrow \text{Act}$. Given the notation above, we also write ATL_{IR}^* to refer to (the standard variant of) ATL^* . As already said, there are several other semantics proposed in the literature, for example referring to agents’ observational capabilities [Schobbens, 2004; Jamroga and van der Hoek, 2004; van der Hoek and Wooldridge, 2002, 2003; Ågotnes, 2004; van Otterloo and Jonker, 2004; Ågotnes, 2006; Jamroga and Ågotnes, 2007; Alur et al., 2002]; to the type of memory available to agents to remember past events; or to the way agents can enforce properties—subjectively or objectively. In order to ensure a uniform notation, following [Schobbens, 2004], we introduce *xy-strategies* for $x \in \{i_s, i_o, I\}$ and $y \in \{r, R\}$ as follows:

IR: $s_a : Q^+ \rightarrow \text{Act}$ such that $s_a(q_0 \dots q_n) \in d(a, q_n)$ for all sequences $q_0 \dots q_n$;

I_r : $s_a : Q \rightarrow Act$ such that $s_a(q) \in d(a, q)$ for all q ;
 $i_o r, i_s r$: like I_r , with the additional constraint that $q \sim_a q'$ implies $s_a(q) = s_a(q')$;
 $i_o R, i_s R$: like IR , with the additional constraint that $h \approx_a h'$ implies $s_a(h) = s_a(h')$.

We note that r stands for memoryless strategies which can be represented by functions $Q \rightarrow Act$, i_s indicates imperfect information under subjective ability, and i_o imperfect information under objective ability. As before, a collective xy -strategy s_A is a tuple of individual xy -strategies s_a , one per agent $a \in A$. We emphasize that $i_s y$ - and $i_o y$ -strategies are defined in the very same way, only the notion of outcome is different, as explained next. The difference between the *objective* and *subjective* outcome, short i_o -outcome and i_s -outcome, respectively, affects the set of initial states when constructing paths. In the former case the agent may not *know* that a uniform strategy achieves the objective; following the given strategy, though, guarantees the objective objectively possibly without the agent being aware of it. This can be interpreted as the perspective of an external observer. In the subjective case, the agent *knows* about a potential winning strategy, i.e. one that achieves the objective; the agent is able to identify and execute it.⁶ Hence, given the current state q , the i_o -outcome considers only paths starting in q , whereas the i_s -outcome considers paths also starting in those states q' which are indistinguishable from q for the agents at stake, i.e. all states q' with $q \sim_A q'$. Formally, we define the x -outcome with $x \in \{I, i_s, i_o\}$ as:

$$\text{out}_{\mathfrak{M}}^x(q, s_A) = \begin{cases} \bigcup_{q \sim_A q'} \text{out}_{\mathfrak{M}}(q', s_A) & \text{if } x = i_s; \\ \text{out}_{\mathfrak{M}}(q, s_A) & \text{else.} \end{cases} \quad (2.2)$$

The general semantic relation \models_{xy} with $x \in \{I, i_s, i_o\}$ and $y \in \{r, R\}$ is now defined by using the appropriate notion of strategy and outcome:

$\mathfrak{M}, q \models_{xy} \langle\langle A \rangle\rangle \varphi$ if, and only if, group $A \subseteq \text{Agt}$ has a collective xy -strategy s_A such that on all paths $\lambda \in \text{out}_{\mathfrak{M}}^x(q, s_A)$ we have that $\mathfrak{M}, \lambda \models_{xy} \varphi$.

2.2.2 The Different Logics and Validities

The different semantics give rise to (potentially) different logics such as:

$$\boxed{\text{ATL}_{IR}^* \quad \text{ATL}_{I_r}^* \quad \text{ATL}_{i_s R}^* \quad \text{ATL}_{i_o R}^* \quad \text{ATL}_{i_s r}^* \quad \text{ATL}_{i_o r}^*}$$

Variants of ATL are defined analogously. These logics capture specific capabilities of agents. For example, $\text{ATL}_{I_r}^*$ assumes that agents have perfect information about the state of the world but have no memory to store past observations: their decisions are based on the current—perfectly identifiable—state only. The set of validities captures general properties of a class of models/games. A formula φ is *valid* wrt. a class of models and a semantic relation, if φ holds in all states in all models of the underlying class of models. Given a logic L for which the class of models and the semantic relation is clear, we write $\varphi \in L$ to denote that φ is a validity; hence, we also identify L with the set of valid sentences. For example, let us consider the formula

$$\psi = \langle\langle 1 \rangle\rangle \mathbf{F}p \leftrightarrow p \vee \langle\langle 1 \rangle\rangle \mathbf{X} \langle\langle 1 \rangle\rangle \mathbf{F}p.$$

It expresses that agent 1 can ensure that p holds eventually if, and only if, p is true now or agent 1 can ensure that in the next state, it can ensure that p holds eventually.⁷ We have that $\psi \in \text{ATL}_{IR}^*$; that is, over the class of (perfect information) concurrent game structures where agents have

⁶ For a detailed discussion, we refer to [Jamroga and van der Hoek, 2004; Bulling and Jamroga, 2014].

⁷ This formula is the fixed-point characterization of operator \mathbf{F} . We will come back to this in Section 2.5.

perfect recall, the fixed-point characterization ψ holds. Intuitively, the formula characterizes the general property over the class of CGSS that agents can construct their strategies for \mathbf{Fp} incrementally. This property is not exclusive to ATL_{IR} : it is also the case that $\psi \in \text{ATL}_{lr}$. Actually, from [Alur et al., 2002] it follows that both logics, ATL_{lr} and ATL_{IR} , share exactly the same general properties, that is $\text{ATL}_{IR} = \text{ATL}_{lr}$. On the other hand, it is easy to give a counterexample showing that ψ is not valid under incomplete information, $\psi \notin \text{ATL}_{i_s R}^*$. A natural question to ask is how exactly all these different variants of ATL are related to each other?

2.2.3 Comparison of Logics and General Properties

In the paper, we investigate this relation in detail. More precisely, given two logics L and L' we investigate whether $L \subsetneq L'$, $L' \subsetneq L$, $L = L'$, or whether L and L' are incomparable. In order to prove that $L \subsetneq L'$ we first show that every L' -satisfiable formula is also L -satisfiable—proving that $L \subseteq L'$. Then, we construct a formula $\varphi \in L'$ and a model \mathfrak{M} in which φ is not true at each state in \mathfrak{M} wrt. the semantics of logic L . That is, we construct a counterexample. Often, the construction of the counterexample seems to be the easier part, at least it seems so if the counter-example is presented. The inclusion part is often more sophisticated. This holds especially if a logic which assumes that agents have perfect recall is compared with one that assumes that agents have only limited memory. Before turning to the more sophisticated case, we give an example illustrating that $\text{ATL}_{i_s r}^* \subsetneq \text{ATL}_{lr}^*$.

To show that $\text{ATL}_{i_s r}^* \subseteq \text{ATL}_{lr}^*$ we observe that every model of ATL_{lr}^* —i.e. every (perfect information) CGS—can be seen as a special ICGS where the epistemic links are assumed to be reflexive loops only. Thus, every ATL_{lr}^* -satisfiable formula is also $\text{ATL}_{i_s r}^*$ -satisfiable. Given the duality of satisfiability and validity, this observation shows that $\varphi \in \text{ATL}_{i_s r}^*$ implies that $\varphi \in \text{ATL}_{lr}^*$. For the strict inclusion, it remains to establish that $\text{ATL}_{lr}^* \not\subseteq \text{ATL}_{i_s r}^*$. Therefore, we consider the formula $\varphi = (\mathbf{p} \vee \langle\langle a \rangle\rangle \mathbf{X} \langle\langle a \rangle\rangle \mathbf{Fp}) \rightarrow \langle\langle a \rangle\rangle \mathbf{Fp}$, the right-to-left direction of the fixed-point characterization of the future-time operator \mathbf{F} , which was already discussed above. Under perfect information the formula is valid. This can be seen by combining the two witnessing strategies associated with the two cooperation modalities in $(\mathbf{p} \vee \langle\langle a \rangle\rangle \mathbf{X} \langle\langle a \rangle\rangle \mathbf{Fp})$ to a single strategy witnessing \mathbf{Fp} . This is not possible under incomplete information, because after the first step the agent may learn about the environment, possibly resolving epistemic limitations. The ICGS \mathfrak{M}_s shown in Figure 2.2 illustrates this⁸. We have that $M_s, q_0 \models_{i_s r} \text{win} \vee \langle\langle a \rangle\rangle \mathbf{X} \langle\langle a \rangle\rangle \mathbf{Fwin}$ but $M_s, q_0 \not\models_{i_s r} \langle\langle a \rangle\rangle \mathbf{Fwin}$. In the former case, a first executes the look action, ending up in states q_4 and q_5 , respectively. In each of these states a , has a memoryless uniform winning strategy to eventually reach state q_2 and to win. However, there is no memoryless uniform strategy to reach the state labelled win from state q_0 —the latter case. In our story⁸, the man cannot directly guess the right door. However, executing the look action would yield the loops $(q_0 q_4)^\omega$ and $(q_1 q_5)^\omega$ if the initial state was q_0 and q_1 , respectively, as the man is bound to memoryless strategies. The result shows that the two logics characterise different general properties of agents.

The comparison of perfect recall and memoryless strategies under incomplete information is more sophisticated. Under perfect information a pointed CGS (\mathfrak{M}, q) , i.e. a model and a state in it, can be unfolded to an infinite, bisimilar tree-shaped CGS $T(\mathfrak{M}, q)$. As a tree does not contain loops, memory does not matter and it follows that:

⁸ The story behind the model is as follows. A man a is in a game show and has to pick one of two doors. The prize is behind one of them. State q_0 (resp. q_1) models that the prize is behind the left (resp. right) door. The man does not know behind which one the prize is. Hence, q_0 and q_1 are indistinguishable for a , $q_0 \sim_a q_1$. However, he is able get a glimpse of the moderator's notes to identify the correct door (states q_4 and q_5). But the man is very nervous and cannot remember this in the next moment.

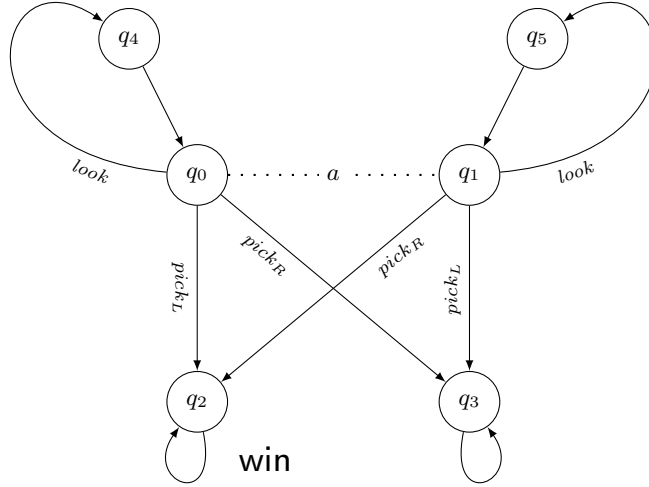


Fig. 2.2. The ICGS \models_s consists of one agent (a) and transitions labeled with a 's actions. The dotted line depicts a 's indistinguishability relation. Automatic transitions (i.e., such that there is only one possible transition from the starting state) are left unlabeled.

$$\mathfrak{M}, q \models_{IR} \varphi \text{ if, and only if, } T(\mathfrak{M}, q) \models_{Ir} \varphi.$$

This shows that every ATL_{IR} -satisfiable formula is also ATL_{Ir} -satisfiable, by taking the tree unfolding of a satisfying model; hence, $\text{ATL}_{Ir}^* \subseteq \text{ATL}_{IR}^*$. The construction under incomplete information follows the same procedure: First, appropriate tree-like structures on which memoryless and perfect-recall strategies coincide are defined. Secondly, it is shown that a model can be unfolded yielding such a tree-like structure. Thirdly, it is proven that the tree unfolding is truth-preserving (i.e. a formula which is true in the original model is also true in the tree-like unfolding and vice versa). The unfolding for imperfect information under objective ability is rather intuitive. Two nodes h and h' in the tree unfolding are indistinguishable for an agent a , if and only if, the histories they represent are indistinguishable in the original model. The procedure for incomplete information under subjective ability, however, requires a new, sophisticated tree-like structure which we coin *pando unfolding* (as strictly speaking, it is not a tree). This is among the main technical results of the paper.

2.2.4 Summary of the results

Using the methods described above, we show that over the class of all (finite and infinite) incomplete information concurrent game structures most of the logics are indeed different, either one is subsumed by another, or they are incomparable. An overview of the results for ATL^* is shown in Figure 2.3. The meaning of these results is threefold. Firstly, they are relevant from a purely theoretical point of view, as logics are often considered as sets of validities. Secondly, as already mentioned above, the results show that the logics characterize different general properties of classes of games. Thirdly, it is a first step towards understanding the satisfiability problems for variants of ATL^* under incomplete information. To the best of our knowledge, satisfiability results are only known for ATL_{IR} and ATL_{IR}^* [Goranko and van Drimmlen, 2006; Walther et al.,

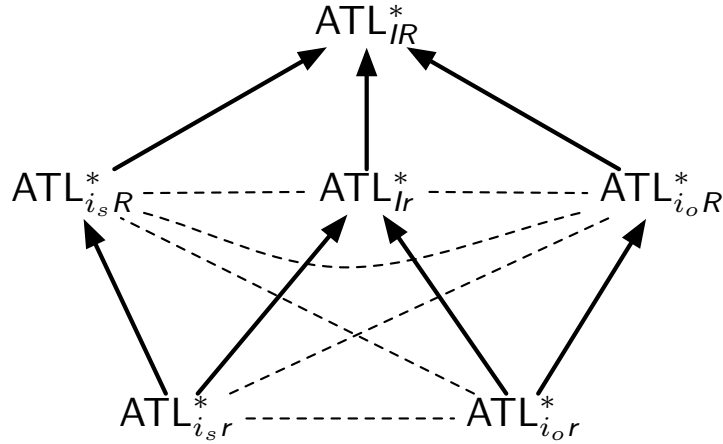


Fig. 2.3. Comparison of validity sets induced by various semantics of ATL^* . Arrows depict strict subsumption of validity sets. Dotted lines connect semantic variants with incomparable validity sets.

2006; Schewe, 2008; Goranko and Shkatov, 2009]. Among the main technical contributions of this work is a (sophisticated) tree-like unfolding, the *pando unfolding*, in the context of subjective incomplete information and perfect recall. We show that the unfolding is truth preserving.

2.3 Agents With Truly Perfect Recall

This section summarizes:

Bulling, N., Jamroga, W., and Popovici, M. (2014). ATL^* with truly perfect recall: Expressivity and validities. In *Proceedings of the 21st European Conference on Artificial Intelligence (ECAI 2014)*, volume 263 of *Frontiers in Artificial Intelligence and Applications*, pages 177–182, Prague, Czech Republic. IOS Press

The logic ATL^*_{iR} , discussed in Section 2.2, allows to model abilities of agents with perfect recall and incomplete information. In particular, this means that agents remember all past events and can take them into consideration when taking decisions. We show that this semantics can be counterintuitive in the context of incomplete information and perfect recall: agents may forget past events although it is assumed that they have perfect recall. This is best illustrated by an example. Consider the ICGS \mathfrak{M}_1 shown in Figure 2.4 modeling a simplified version of a *shell game*. Our version of the shell game consists of two players, the *shuffler* s and the *guesser* g . In state q_0 the shuffler places a ball in the left or the right shell, modeled by actions put_L and put_R , respectively. At the beginning in q_0 , the shells are open, and the guesser can see the location of the ball. If the shuffler turns the shells over, the ball will become hidden; actually, this is the only choice that he has in q_0 . Thus, the guesser cannot distinguish the states q_2 and q'_2 , which is modeled by $q_2 \sim_g q'_2$. It is important to note that epistemic relations capture observational limitations only and not the evolving knowledge of agents. This is also an important distinction between the computational and the behavioral structure of a model. The guesser wins if he picks up the shell containing the ball. Even this very simple example is rich enough to highlight the following limitations of ATL^*_{iR} :

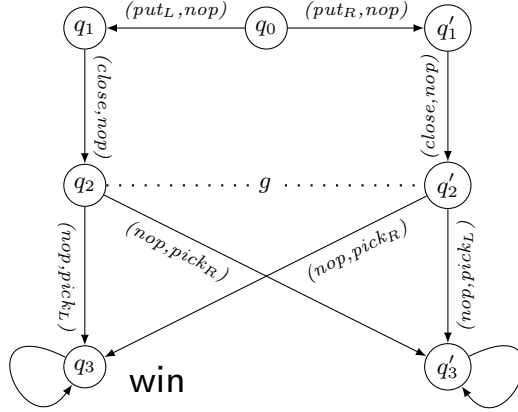


Fig. 2.4. The ICGS \mathfrak{M}_1 describes a variant of a *shell* game. Tuples (α_1, α_2) , e.g. (put_L, nop) , represent the action profiles. α_1 denotes an action of player s —the shuffler—and action α_2 of player g —the guesser. The dotted line represents g 's indistinguishability relation; reflexive loops are omitted. State q_3 is labelled with the only proposition *win*. For example, when the guesser plays action $pick_R$ in state q_2 the game proceeds to state q_3 . *nop* indicates the “do nothing” action.

- On the one hand, the guesser has a strategy to win against all moves of the shuffler s : $\mathfrak{M}_1, q_0 \models_{iR} \langle\langle g \rangle\rangle \mathbf{F} \text{win}$. This is so, because s has perfect information about q_0 . Due to the semantics of ATL_{iR}^* and as there are no nested cooperation modalities the epistemic link between q_2 and q_2' is irrelevant. Intuitively, while playing the game the shuffler learns to distinguish q_2 and q_2' .
- On the other hand, the shuffler has a strategy to enforce that the guesser will not be able to win: $\mathfrak{M}_1, q_0 \models_{iR} \langle\langle s \rangle\rangle \mathbf{F} \neg \langle\langle g \rangle\rangle \mathbf{F} \text{win}$. This is clearly counterintuitive to the previous property. Here, it is important to note that if a formula of type $\langle\langle A \rangle\rangle \varphi$ is interpreted in a state q , then all states indistinguishable from q for A must be taken into consideration as well. In the specific example, if $\langle\langle g \rangle\rangle \mathbf{F} \text{win}$ is evaluated in q_2 then the formula is also evaluated in q_2' being an epistemic alternative of q_2 . Intuitively, during the play the shuffler learns to distinguish q_2 and q_2' *but* in case of nested cooperation modalities the shuffler forgets what he has learnt.

This problem is due to the way nested modalities are treated in the semantics of ATL_{iR}^* , and indeed all other variants of ATL considered so far. As the example showed, when evaluating a subformula $\langle\langle A \rangle\rangle \psi$ the group A “forgets” what has happened so far.

The *no-forgetting semantics* which we propose in the paper resolves this counter-intuitive behavior. In the example, in q_2 or q_2' the agents remember whether the very state has been reached via state q_1 or q_1' , respectively. As a consequence, in the new semantics we have that $\neg \langle\langle s \rangle\rangle \mathbf{F} \langle\langle g \rangle\rangle \mathbf{F} \text{win}$ in q_0 because the two histories $q_0 q_1 q_2$ and $q_0 q_1' q_2'$ —now remembered by the guesser—are distinguishable and are taken into account when evaluating the subformula $\langle\langle g \rangle\rangle \mathbf{F} \text{win}$.

Formally, the *no-forgetting semantics* is defined by the relation⁹ \models_x^{nf} , $x \in \{i, I\}$, again for the perfect (I) and imperfect information (i) cases, where i corresponds to subjective ability in terms of Section 2.2. Differently from above, formulae are interpreted over triples consisting of a model, a history/path and an index $k \in \mathbb{N}_0$ which identifies the current state on the path. The subhistory of a path λ up to k , denoted by $\lambda[0, k-1]$, encodes the past; the subpath starting

⁹ We omit a capital R as the semantics is only defined for perfect recall strategies.

after k , denoted by $\lambda[k+1, \infty]$, the future; and the state at the k th position, $\lambda[k]$, the current state. The crucial part of this semantics is that the agents can learn from past events encoded in $\lambda[0, k-1]$. The semantic clauses are defined as follows:

$$\begin{aligned}
\mathfrak{M}, \lambda, k &\models_x^{nf} p \text{ iff } \lambda[k] \in \Pi(p) \text{ for } p \in \Pi; \\
\mathfrak{M}, \lambda, k &\models_x^{nf} \neg\varphi \text{ iff } \mathfrak{M}, \lambda, k \not\models_x^{nf} \varphi; \\
\mathfrak{M}, \lambda, k &\models_x^{nf} \varphi_1 \wedge \varphi_2 \text{ iff } \mathfrak{M}, \lambda, k \models_x^{nf} \varphi_1 \text{ and } \mathfrak{M}, \lambda, k \models_x^{nf} \varphi_2; \\
\mathfrak{M}, \lambda, k &\models_x^{nf} \langle\langle A \rangle\rangle\varphi \text{ iff there exists an } xR\text{-strategy } s_A \text{ such that, for all paths } \lambda' \in \text{plays}_{\mathfrak{M}}^x(\lambda[0, k], s_A), \\
&\quad \mathfrak{M}, \lambda', k \models_x^{nf} \varphi; \\
\mathfrak{M}, \lambda, k &\models_x^{nf} \mathbf{X}\varphi \text{ iff } \mathfrak{M}, \lambda, k+1 \models_x^{nf} \varphi; \\
\mathfrak{M}, \lambda, k &\models_x^{nf} \varphi_1 \mathbf{U}\varphi_2 \text{ iff there exists } i \geq k \text{ such that } \mathfrak{M}, \lambda, i \models_x^{nf} \varphi_2 \text{ and } \mathfrak{M}, \lambda, j \models_x^{nf} \varphi_1 \text{ for all} \\
&\quad k \leq j < i.
\end{aligned}$$

where

$$\text{plays}_{\mathfrak{M}}^x(h, s_A) = \begin{cases} \bigcup_{h \approx_A h'} \{h' \circ \lambda \mid \text{out}_{\mathfrak{M}}^x(h'[last], s_A)\} & \text{for } x = i \\ \{h \circ \lambda \mid \text{out}_{\mathfrak{M}}^x(h[last], s_A)\} & \text{for } x = I \end{cases}, \quad (2.3)$$

$h[last]$ refers to the last state of history h , respectively, and $h \circ \lambda$ denotes the concatenation of history h and path λ . Given a state formula φ and a history h , we write $\mathfrak{M}, h \models_x^{nf} \varphi$ iff $\mathfrak{M}, \lambda, k \models_x^{nf} \varphi$ for any path $\lambda \in \Lambda$ with $\lambda[0, k] = h$. We coin the resulting logics $\text{ATL}_{nf, x}^*$ for $x \in \{i, I\}$. Note that $\text{plays}_{\mathfrak{M}}^x(\cdot, \cdot)$ is very similar to $\text{out}_{\mathfrak{M}}^x(\cdot, \cdot)$, but it keeps track of past events; paths do no longer only encode the future.

We reconsider our example in a more formal way and show that $\mathfrak{M}_1, q_0 \models_i^{nf} \neg\langle\langle s \rangle\rangle \mathbf{F}\neg\langle\langle g \rangle\rangle \mathbf{F}\text{win}$. That is, for any strategy of shuffler s there is a path such that in all states on it, g can ensure to eventually win. In particular, player g can ensure to reach the winning state q_3 from state q_2 as well as from q'_2 . To see this, suppose player s decided to reach state q_2 via history $q_0q_1q_2$ (the other case is symmetric). Then, $\text{plays}_s^i(q_0q_1q_2, s_g) = \{q_0q_1q_2q_3^\omega\}$ where s_g is the (uniform) strategy selecting pick_L after $q_0q_1q_2$ —note the difference to $\text{out}_s^i(q_2, s_g)$ which contains two different paths¹⁰. Clearly, we have that $\mathfrak{M}_1, q_0q_1q_2 \models_i^{nf} \langle\langle g \rangle\rangle \mathbf{F}\text{win}$.

The example suggests that the new semantics allows to express properties which are not expressible in the standard semantics. In the paper we investigate the precise relation between the logics' expressive and distinguishing power, as well as the general properties they describe, in the sense of Section 2.2. Expressiveness refers to the logic's power to characterize specific properties over a class of models, for example the reflexivity of models. Distinguishing power refers to the capability to distinguish specific models; here, the formula may not be the same across all models but can be specific to the models under consideration. We note that if a logic is more expressive than another one, then the same holds for the logic's distinguishing power; the converse is not necessarily true.

Unsurprisingly, both semantics are equivalent under perfect information. Thus, the logics ATL_i^* and $\text{ATL}_{nf, i}^*$ are equally expressive, have the same distinguishing power, and have the same set of validities ($\text{ATL}_i^* = \text{ATL}_{nf, i}^*$). Secondly, we consider incomplete information. We show that the logics ATL_i^* and $\text{ATL}_{nf, i}^*$ have *incomparable* distinguishing and expressive powers. To show that $\text{ATL}_{nf, i}^*$ is no more distinguishing than ATL_i^* we consider the two models shown in Figure 2.5. There is no $\text{ATL}_{nf, i}^*$ -formula that can distinguish (\mathfrak{M}_3, a_0) from (\mathfrak{M}'_3, a_0) . It is easy to observe that the only way to distinguish both pointed models would be to evaluate a state formula in states a_1 or b_1 . The paths that start in (\mathfrak{M}_3, a_0) are identical to those that start in (\mathfrak{M}'_3, a_0) . Moreover, in both models all histories that pass through a_1 are distinguishable from those that

¹⁰ Note that in this case $s_g(q_2) = s_g(q'_2) = \text{pick}_L$.

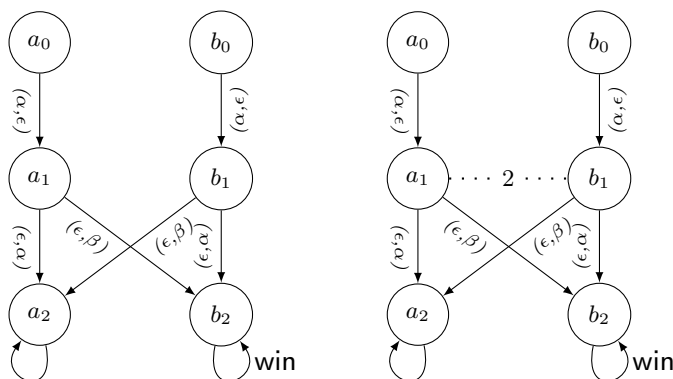


Fig. 2.5. \mathfrak{M}_3 (resp. \mathfrak{M}'_3) is the iCGS shown on the left-hand-side (resp. right-hand-side) of the Figure.

pass through b_1 , because the former start in a_0 while the latter start in b_0 . Thus, there is no way that a formula can distinguish the pointed models under the no-forgetting semantics. But both models can be distinguished by ATL_i^* : $\mathfrak{M}_3, a_0 \models_i \langle\langle 1 \rangle\rangle \mathbf{X} \langle\langle 2 \rangle\rangle \mathbf{X} \text{win}$ and $\mathfrak{M}'_3, a_0 \not\models_i \langle\langle 1 \rangle\rangle \mathbf{X} \langle\langle 2 \rangle\rangle \mathbf{X} \text{win}$. In the latter case player 2 “forgets” that the game started in state a_0 when the nested cooperation modality is evaluated. In \mathfrak{M}'_3 the player cannot distinguish state a_1 from b_1 when evaluating the nested formula and there is no uniform strategy winning from a_1 as well as from b_1 in \mathfrak{M}'_3 . The reasoning that ATL_i^* is no more distinguishing than $\text{ATL}_{\text{nf},i}^*$ follows the same lines but the two models are slightly more sophisticated. Although both logics are incomparable regarding expressive and distinguishing power, they are comparable on the level of validities: the logic $\text{ATL}_{\text{nf},i}^*$ defines a more specific class of games than ATL_i^* ; we have that $\text{ATL}_i^* \subsetneq \text{ATL}_{\text{nf},i}^*$.

In summary, the main contributions of the paper are the following:

- We propose a no-forgetting semantics for ATL^* , fixing a conceptually counter-intuitive behavior.
- We show that the new and old semantics coincide for perfect information.
- We show that both semantics have incomparable expressive and distinguishing power under incomplete information.
- In the context of validities, we show that the no-forgetting semantics describes a more specific class of games (games in which players do not forget past events).

2.4 Combining Quantitative and Qualitative Reasoning

This section summarizes:

Bulling, N. and Goranko, V. (2013). How to be both rich and happy: Combining quantitative and qualitative strategic reasoning about multi-player games (extended abstract). In *Proc. of the 1st International Workshop on Strategic Reasoning, EPTCS*, pages 33–41, Rome, Italy

ATL^* and its variants are purely qualitative, allowing to reason about qualitative objectives. There are only a few extensions of ATL^* that we know of which include quantitative aspects, e.g. resource-bounded settings proposed in [Bulling and Farwer, 2010; Alechina et al., 2011; Della Monica et al., 2011]. However, in the domain of infinite games quantitative aspects play a prominent role, e.g. in deterministic or stochastic *infinite games on graphs* [de Alfaro et al., 2007], [Chatterjee et al., 2011], [Chatterjee and Henzinger, 2012]; in purely quantitative *repeated*

games; in *stochastic games with quantitative objectives* [Peters and Vrieze, 1987]; and in *mean-payoff and energy parity games* [Chatterjee et al., 2005], [Chatterjee and Doyen, 2012], [Bohy et al., 2013]. In general, quantitative aspects are especially important in classical decision making where agents want to maximize their expected utility. In our work we combine both traditions and propose *Quantitative ATL**, *QATL** in short.

In the following we briefly review the logical setting. Firstly, we fix a simple language of arithmetic constraints which is built over variables $V_{\text{Agt}} = \{v_a \mid a \in \text{Agt}\}$ referring to accumulated payoffs of the players at a given state. An arithmetic constraint is of type $t_1 * t_2$ where $*$ $\in \{<, \leq, =, \geq, >\}$ and each arithmetic term t_i is essentially constructed from V_{Agt} allowing addition. For example, $v_1 + v_2 \geq v_3$ expresses that the sum of the accumulated payoffs of agents 1 and 2 is greater or equal to the accumulated payoff of agent 3. We also allow Boolean combinations of such arithmetic constraints. The language of *QATL** extends *ATL** with such arithmetic constraint formulae *ac*:

$$\varphi ::= p \mid \mathbf{ac} \mid \neg\varphi \mid \varphi \wedge \varphi \mid \langle\langle A \rangle\rangle\gamma \text{ and } \gamma ::= \varphi \mid \neg\gamma \mid \gamma \wedge \gamma \mid \mathbf{X}\gamma \mid \mathbf{G}\gamma \mid \gamma \mathbf{U}\gamma.$$

The logic allows to express strategic properties over qualitative as well as quantitative statements. A typical formula is $\langle\langle 1, 2 \rangle\rangle \mathbf{F}(p \wedge v_1 > 100 \wedge v_2 > 100)$, expressing that coalition $\{1, 2\}$ can eventually guarantee p and to receive (at the same state) an accumulated payoff of more than 100 each. Models of the logic extend CGSs with payoffs. Each transition—corresponding to an action profile—is associated with a set of payoffs, one for each agent. A global state is a *configuration* consisting of the system state and a tuple of accumulated payoffs, one for each agent. Additionally, each state is assigned a guard which can enable and disable specific actions and thus transitions, depending on the agents’ accumulated payoffs. For instance, it could be specified that specific actions are only enabled for those players that have a positive accumulated payoff. The general setting can be restricted in many ways affecting the computational properties of the logic.

The payoffs associated with each action profile allow to consider the new model as a guarded CGS in which each state is assigned a normal form game. This is illustrated in Figure 2.6. The

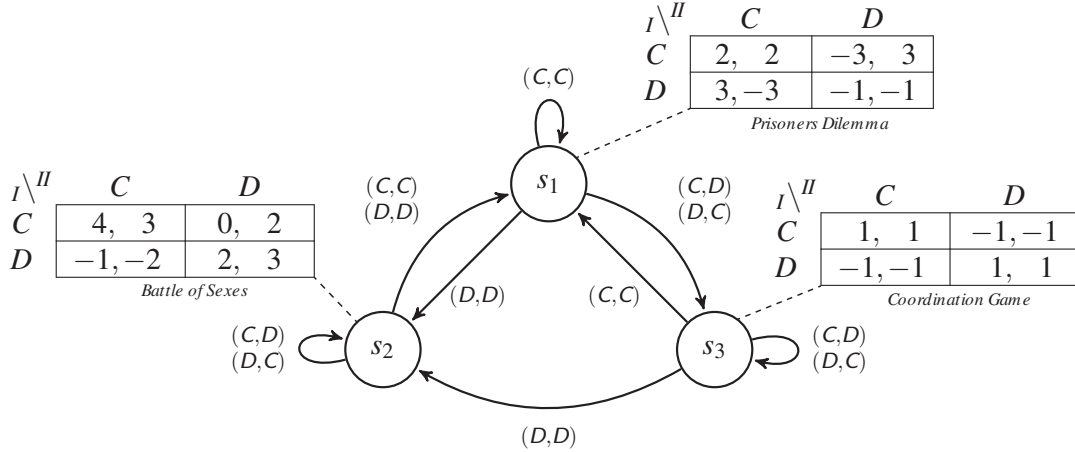


Fig. 2.6. A simple guarded CGS with payoffs.

model consists of 2 players, I and II, and 3 states, where at each state each player has 2 possible

actions: C (cooperate) and D (defect). The normal form games associated with the states are versions of the Prisoner’s Dilemma at state s_1 , Battle of the Sexes at state s_2 and Coordination Game at state s_3 , respectively. The guards at each state for both players are identical: a player can apply any action if it has a positive current accumulated payoff; may only apply action C if it has accumulated payoff 0; and must play an action maximizing its minimum payoff in the current game if the accumulated payoff is negative. The initial payoffs of both players are 0.

In this setting, a *strategy* can take into account the accumulated payoff of a player, of other players, and of states and history. The only constraint is that the choices assigned by a strategy need to respect the guards, meaning that a chosen strategy must be enabled at the very state. The used notion of strategy affects the complexity and decidability of the logic, in particular, with respect to model checking. In our example from Figure 2.6 a possible strategy for both players could be to always cooperate, yielding the outcome path $(s_1, 0, 0), (s_1, 2, 2), (s_1, 4, 4), \dots$. Each tuple consists of the state of the model, the accumulated payoff of player I in that state and the one of player II , respectively. Another strategy could be to cooperate in the first round and then to defect. The play continues to s_2 , where player I chooses to defect whereas II cooperates. Then I must cooperate while II must defect, due to the definition of the guards. In the next round I can choose any action. Thus a possible play is: $(s_1, 0, 0), (s_1, 2, 2), (s_2, 1, 1), (s_2, 0, -1), (s_2, 0, 1), (s_2, 0, 3), (s_2, 0, 5), \dots$. QATL* can now be used to reason about players’ ability in a qualitative and quantitative way. For example, in configuration $(s_1, 0, 0)$ the following two formulae hold where p_i is an atomic proposition true only at state s_i , for each $i = 1, 2, 3$: $\langle\langle\{I, II\}\rangle\rangle\mathbf{F}(p_1 \wedge v_I > 100 \wedge v_{II} > 100) \wedge \langle\langle\{I, II\}\rangle\rangle\mathbf{X}\langle\langle\{II\}\rangle\rangle(\mathbf{G}(p_2 \wedge v_I = 0) \wedge \mathbf{F} v_{II} > 100)$ and $\neg\langle\langle\{I\}\rangle\rangle\mathbf{G}(p_1 \vee v_I > 0) \wedge \neg\langle\langle\{I, II\}\rangle\rangle\mathbf{F}(p_3 \wedge \mathbf{G}(p_3 \wedge (v_I + v_{II} > 0)))$.

Unsurprisingly, the models are too rich and the language of QATL* is too expressive to expect good computational properties and even decidability of model checking as well as satisfiability checking in the general case. We consider first results about the (un)decidability of the logical framework. Our main contributions are:

- Proposal of Quantitative ATL* and quantitative extension of CGSSs.
- An approach combining three areas: logic, game theory, and computer science.
- First (un)decidability result.

2.5 Alternating-Time Epistemic μ -Calculus

This section summarizes:

Bulling, N. and Jamroga, W. (2011). Alternating epistemic mu-calculus. In *IJCAI 2011, Proceedings of the 22nd International Joint Conference on Artificial Intelligence, Barcelona, Catalonia, Spain, July 16-22, 2011*, pages 109–114, Barcelona, Spain. IJCAI/AAAI

An important feature of ATL* and ATL under perfect information are the fixed-point formulae characterizing properties of the temporal operators. For example, for the “now or sometime in the future” operator \mathbf{F} the characterization $\langle\langle A \rangle\rangle\mathbf{F}\mathbf{p} \leftrightarrow \mathbf{p} \vee \langle\langle A \rangle\rangle\mathbf{X}\langle\langle A \rangle\rangle\mathbf{F}\mathbf{p}$ holds: A can eventually enforce \mathbf{p} if, and only if, \mathbf{p} is true now or A can ensure that in the next moment A can ensure that \mathbf{p} holds now or in the future. Such a characterization allows to decompose complex strategic reasoning into a simpler reasoning; put another way, strategies can be constructed step-by-step. This is important especially for efficient model checking algorithms. These characterizations do usually not hold for imperfect information variants of ATL*, as already illustrated in Section 2.2. Conceptually, this also means that having a strategy to achieve φ does not imply that the

agents will be able to *recompute* a (or the) winning strategy while executing it. Motivated by this observation we add fixed-point operators to the “next-time” fragment of ATL_{IR} ; or put differently, we consider an epistemic extension of the *alternating μ -calculus* (AMC) proposed by Alur et al. [2002]. Consistent with the notations used above, we call the logic *alternating epistemic μ -calculus* (AMC_i) and study its properties. The logic is defined as:

$$\varphi ::= \mathbf{p} \mid X \mid \neg\varphi \mid \varphi \vee \psi \mid \langle A \rangle \varphi \mid \mu X(\varphi) \mid K_a \varphi$$

where $A \subseteq \text{Agt}$, $\mathbf{p} \in \Pi$, X is a variable ranging over sets of states and each φ in $\mu X(\varphi)$ is *X-positive*, i.e. each free occurrence of X in φ is under the scope of an even number of negations in φ . Operator $\mu X(\varphi)$ is the least fixed-point operator. To define the semantics formally, we need the notion of valuation which is a function $\mathcal{V} : \text{Var} \rightarrow 2^Q$. It assigns to a variable X the states in which X is true. Given a variable X and a set $Z \subseteq Q$ of states we define

$$\mathcal{V}[X := Z](Y) = \begin{cases} \mathcal{V}(Y) & \text{if } X \neq Y; \\ Z & \text{else.} \end{cases}$$

That is, the valuation $\mathcal{V}[X := Z]$ equals \mathcal{V} for all variables different from X and assigns Z to X . Truth of AMC_i -formulae is given by the denotation function $\llbracket \cdot \rrbracket_{\mathfrak{M}}^{\mathcal{V}}$ that maps AMC_i -formulae to the sets of states satisfying the formula (i.e. $\llbracket \varphi \rrbracket_{\mathfrak{M}}^{\mathcal{V}} \subseteq Q$) where \mathfrak{M} is an ICGS and \mathcal{V} is a valuation. Now, the semantics of the least fixed-point operator is the least fixed-point of the function $f : 2^Q \rightarrow 2^Q$ with $f(Z) = \llbracket \mu X(\varphi) \rrbracket_{\mathfrak{M}}^{\mathcal{V}[X := Z]}$. The fixed-point operator is very expressive and allows to define the standard temporal operators under perfect information [Alur et al., 2002]. For example, $\langle\langle A \rangle\rangle \mathbf{F}\psi$ can be defined as $\mu X(\psi \vee \langle A \rangle X)$. It is well-known that the alternation-free fragment of the AMC is more expressive than ATL_{IR} , where the alternation-free fragment imposes restrictions on the construction of AMC-formulae. In this work we study the relation under incomplete information where the semantics of the cooperation modality is given as follow:

$$\llbracket \langle A \rangle \varphi \rrbracket_{\mathfrak{M}}^{\mathcal{V}} = \{q \mid \exists s_A \in \Sigma_A^{ir} \forall \lambda = q_0 q_1 \dots \in \text{out}^{ir}(q, s_A)(q_1 \in \llbracket \varphi \rrbracket_{\mathfrak{M}}^{\mathcal{V}})\}$$

where Σ_A^{ir} denotes the set of collective *ir*-strategies of group A , and of the knowledge operator as

$$\llbracket K_a \varphi \rrbracket_{\mathfrak{M}}^{\mathcal{V}} = \{q \mid \forall q'(q \sim_a q' \text{ implies } q' \in \llbracket \varphi \rrbracket_{\mathfrak{M}}^{\mathcal{V}})\}.$$

That is, $\llbracket \langle A \rangle \varphi \rrbracket_{\mathfrak{M}}^{\mathcal{V}}$ is the set of states from which agents A have a collective uniform strategy to enforce a state in which φ holds in the next moment.

To illustrate the logic we consider the two models shown in Figure 2.7. The story behind model \mathfrak{M} is as follows : A robot is in its initial position (q_0) and needs to find its way to its destination state q_2 labelled \mathbf{p} . To reach the destination the robot needs to cross a tunnel in which it has no connection to the base (q_1) and can thus not access its stored planning data. In the tunnel the robot can only rely on its imprecise GPS signal. As a result, it does not know whether its exact location is q_1 or q'_1 . Only q_1 allows the robot to reach the destination q_2 .

We have that $\mathfrak{M}, q_0 \models_{ir} \langle\langle robot \rangle\rangle \mathbf{F}\mathbf{p}$, so the robot has a plan to reach the destination. It knows *now* that everything will be fine, but it also knows that it will loose the connection on the way, which may prevent the robot from reaching its destination. The stronger kind of ability is captured by the alternation-free AMC_i -formula $\mu X(\mathbf{p} \vee \langle robot \rangle X)$, which is *not* true in \mathfrak{M}, q_0 . The minimal fixed-point of the formula is $\{q_2\}$. The reason is that there is no uniform strategy in q_1 which subjectively ensures to end up in a state where \mathbf{p} holds: from the robot’s perspective state q'_1 is an epistemic alternative to q_1 .

The example suggests that there are some properties expressible in the alternation-free AMC_i which are not expressible in ATL_{ir} . Indeed, this is the case. Surprisingly however, it is not the case

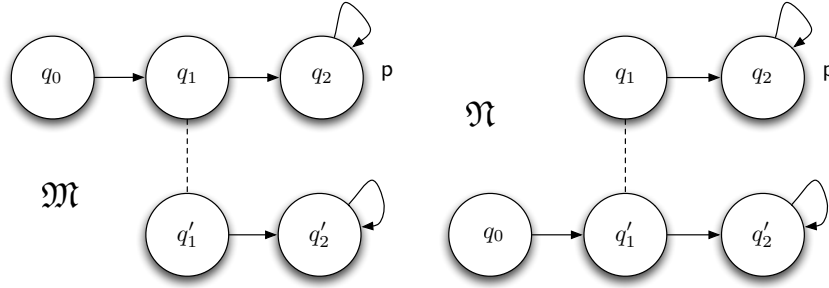


Fig. 2.7. Models \mathfrak{M} and \mathfrak{N} , each with a single agent 1.

that the new logic is strictly more expressive than ATL_{ir} . We prove that AMC_i is incomparable in expressive power to ATL_{ir} as well as to ATL_{iR} . Actually, the models \mathfrak{M} and \mathfrak{N} from Figure 2.7 cannot be distinguished by AMC_i but they can by ATL_{ir} . Thus, we obtain a new notion of strategic ability not expressible in standard epistemic variants of ATL.

We also analyse the model checking complexity of the new logic. We prove that for a restricted case of groups of up to two agents, the alternation-free AMC_i has better computational properties than its corresponding variant of ATL under incomplete information. This can be important for settings in which only two agents act together at the same time, which is, for example, often the case in the analysis of security protocols. In summary, the main contributions of this paper are:

- We propose an epistemic variant of AMC, called AMC_i .
- We show that the alternation-free fragment of AMC_i is incomparable to ATL_{ir} and ATL_{iR} .
- We give characterizations of new strategic properties.
- We also prove that model checking the alternation-free fragment of AMC_i can be done in polynomial time for small coalitions; for larger groups of agents, the verification complexity is in Δ_2^P , as for ATL_{ir} .

2.6 Taming the Complexity of Linear Time BDI Logics

This section summarizes:

Bulling, N. and Hindriks, K. V. (2011). Taming the complexity of linear time BDI logics. In *Proceedings of the 10th International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2011)*, pages 275–282, Taipei, Taiwan. ACM Press

Among the main application areas of logic, especially temporal and strategic logic, are system modeling/specification/verification [Clarke et al., 1999; Baier and Katoen, 2008; Bulling et al., 2010] and automated reasoning [Fisher, 2008; Fisher et al., 2005; Bulling et al., 2015; Fagin et al., 1995a]. A challenge is to cope with the high computational complexity that is often involved when dealing with logic. The complexity is especially crucial in the context of automated reasoning. When agents use logical methods for reasoning, the computational complexity of satisfiability checking is important as agents have to react in time. Agents’ mental states play a decisive role in the reasoning cycle: agents have to reason about other agents’ beliefs, desires and intentions, in particular when working in teams they need to reason about other agents’ mental states [Dunin-Keplicz and Verbrugge, 2006]. The same holds for establishing joint commitments [Jennings, 1993; Cohen et al., 1997], and to collaborate/cooperate with others [Jennings, 1993; Tambe, 1997;

Cohen et al., 1997; Dunin-Keplicz and Verbrugge, 2006]. Socio-cognitive robotics and human-robot teamwork are other areas where reasoning about mental states and social behavior is essential [Kennedy et al., 2009]. In principle, logical approaches are capable to be used for these tasks but in practice little use is made of them [Cohen et al., 1997; Rao, 1996; Dziubinski et al., 2007]. Arguably, one reason is the logics’ inherent complexity which has been well studied for logics of time and knowledge. In this work we propose a logic which is, on one hand, expressive enough to be used for reasoning about agents’ mental states and, on the other hand, has “good” computational properties. For the latter case, we investigate restrictions on the general setting.

Our work is based on BDI_{LTL} [Rao, 1996]. The logic provides means to talk about linear-time, as well as informational and motivational attitudes of agents. The latter are captured by modal operators for beliefs, desires and intentions. Formulae of the logic are built according to the grammar:

$$\varphi ::= p \mid \neg\varphi \mid \varphi \wedge \varphi \mid \varphi \mathbf{U}\varphi \mid \mathbf{X}\varphi \mid B_i\varphi \mid D_i\varphi \mid I_i\varphi$$

where i refers to an agent from Agt . The temporal operators \mathbf{U} and \mathbf{X} have their standard interpretation. $B_i\varphi$, $D_i\varphi$, and $I_i\varphi$ expresses that agent i believes, desires, and intends φ , respectively. Operators can also be nested to talk about other agents’ mental states. For example, the formula $B_i B_j \mathbf{X} I_k p$ specifies that agent i believes that agent j believes that in the next moment agent k intends p . One cannot expect the complexity of satisfiability checking BDI_{LTL} to be lower than for the modal and temporal logics BDI_{LTL} is comprised of. So, a good starting point is to analyse existing complexity results and whether they can be applied to the proposed setting. In [Halpern and Moses, 1992] the complexity of single- and multi-agent logics for knowledge and belief are studied. Depending on the properties of the modal operators and the number of agents the results range from **NP**- to **PSPACE**-completeness, and even **EXPTIME**-completeness in the case of common knowledge. Also, Ladner’s theorem [Blackburn et al., 2001b] provides bounds on the complexity for modal logics between **K** and **S4**; they are **PSPACE**-complete. So, in the general setting one cannot hope for better complexity results. However, it has been shown that bounding the number of propositional variables or the nesting depth of modal operators can yield logics with better computational properties. In particular, if both restrictions are imposed on the logic satisfiability checking could be done in linear time. In Table 2.1 we give an overview of the various complexity results. We use $md \leq c$, $c \in \mathbb{N}_0$, to denote the restriction to formulae, the nesting of modal operators of which is bounded by c . We use $|II|$ to denote the number of propositions. The first cell of a row is understood as a constraint, e.g. $|II| \leq c$, $md \leq c'$ characterizes the case in which the number of propositions and the modal depth is bounded by natural numbers c and c' , respectively.

	K45, KD45, S5	K, KD _n , K45 _n , KD45 _n , S5 _n
no constraints	NP -compl.	PSPACE -compl.
$ II \leq c$	linear time	PSPACE -compl.
$md \leq c$	NP -compl.	NP -compl.
$ II \leq c$, $md \leq c'$	linear time	linear time

Table 2.1. Overview of complexity of satisfiability checking for multi-agent modal logics.

Similar results exist for the temporal fragment of BDI_{LTL} . The temporal logic **LTL** has a **PSPACE**-complete satisfiability problem. Restricted settings can be obtained as before by restricting the number of propositions or the depth of the temporal nesting (denoted by td); additionally, the available temporal operators can be restricted [Demri and Schnoebelen, 1997]. An

overview of some complexity results is given in Table 2.2. Combinations of time and knowledge

	LTL	LTL(U)
$ II \leq c, td \leq c'$	L	L
td=0	NP -compl.	NP -compl.
$ II = 1$	PSPACE -compl.	P
td = 2	PSPACE -compl.	PSPACE -compl.

Table 2.2. Overview of complexity of satisfiability checking for temporal logics. We denote by LTL(U) the fragment with U being the only temporal operator.

have been analysed in [Halpern and Vardi, 1989]. BDI_{LTL} allows for modal operators with properties different from classical knowledge, i.e. S5. Therefore, we investigate generic variants $\text{BDI}_{\text{LTL}}^{X,Y,Z}$ where $X, Y, Z \in \{K, \text{KD}, \text{KD45}, \text{S4}, \text{S5}\}$. For example, the logic $\text{BDI}_{\text{LTL}}^{\text{S5}, \text{KD}, \text{KD}}$ combines knowledge (S5), consistent desires (KD), and consistent intentions (KD). Models of BDI_{LTL} are given by interpreted systems [Fagin et al., 1995b] including an accessibility relation over points (r, m) , i.e. an infinite sequence of states r —a *run*—and a time point m on r , for each of the modal operators in addition to a temporal accessibility relation. The semantic clause for B_i^φ is, for example, defined as follows:

$$\mathfrak{M}, r, m \models B_i \varphi \text{ iff } \mathfrak{M}, r', m' \models \varphi \text{ for all } (r', m') \text{ with } (r, m) \mathcal{B}_i(r', m').$$

$B_i \varphi$ expresses that agent i believes φ in (r, m) if, and only if, φ holds in all points (r', m') which i believes to be an alternative to (r, m) . In the work we aim at identifying fragments of BDI_{LTL} which are expressive enough to allow reasoning about mental states and which have an “acceptable” complexity. Given that we can often not avoid propositional reasoning we consider **NP** as acceptable complexity class. In line with the discussion above we identify the following fragments of BDI_{LTL} which may still be in **NP**:

- the fragment with finitely many propositional atoms, limited temporal depth, and bounded nesting of other modal operators representing mental attitudes, and
- the fragment with no nesting of temporal operators and bounded nesting of other modal operators representing mental attitudes.

In the paper, we describe a generic tableau-based method for deciding the satisfiability of $\text{BDI}_{\text{LTL}}^{X,Y,Z}$ -formulae. That is, the tableau procedure takes into account the specific instantiations of X, Y , and Z . We show that the tableau-procedure is sound and complete and that it is **PSPACE**-complete in the general setting. Additionally, we analyse a restricted setting which is **NP**-complete, and another one that can be solved in deterministic logarithmic space. Apart from the complexity results we also postulate minimality criteria that a logic for reasoning about agents’ mental states should satisfy. In summary, our main contributions are:

- A generic sound tableaux-based satisfiability procedure for BDI_{LTL} .
- Complexity results for various fragments of BDI_{LTL} which range from **L** to **PSPACE**.
- Analysis of requirements for logics for reasoning about agents’ mental states.

Coordination and Control of Multi-Agent Decision Making

In Chapter 2 we considered strategic logics, in particular variants of ATL, to describe, specify and verify MASs [Baier and Katoen, 2008; Bulling et al., 2010; Clarke et al., 1999], and to reason about strategic abilities of agents [Bulling et al., 2015; Fagin et al., 1995a; van Benthem et al., 2015]. The logics have a descriptive flavor; they do not provide immediate means to *change* a system’s state or the behavior of agents. This is sufficient when one wants to verify whether a system satisfies a property. But what to do, if the answer is negative?

In smart grids the activities of electricity producers need to be coordinated. In case electricity plants are part of the same company this means to essentially implement control strategies. If the production takes place at different companies or at the customer side (they may have their own solar modules and inject electricity into the smart grid) the diverse interests have to be taken into consideration. Regulations or incentives may be needed to influence the stakeholders’ activities to ensure a reliable and stable power supply. Flexible tariffs can be used to incentivize customers to change their profile accordingly. Clearly, there are limits to the customers’ willingness or possibilities to change their behavior. Also, the behavior of the customers need to be monitored. Smart meters are used to record the users’ power consumption. This information has to be analysed to develop appropriate control strategies, including the prediction of the expected power consumption. In this section we investigate formal methods to analyse whether agents can be incentivized to change their behavior, and also whether violations of regulations will be monitored. We investigate formal tools to influence the decision making of agents and thus to actually change the emerging behavior of a MAS.

One approach we consider is based on *normative multi-agent systems* (NORMASs) [Boella et al., 2006; Andrighetto et al., 2013]. Jones and Sergot [1993], Shoham and Tennenholtz [1992, 1995], and Moses and Tennenholtz [1995] have already proposed norms and social laws as means to coordinate (social) systems. A classical example of a norm is the traffic law “right has right-of-way” which *coordinates* traffic. Starting with this work, logical approaches have been used to model and to reason about norms and their effects [van der Hoek et al., 2007; Ågotnes et al., 2007, 2009; Wooldridge and van der Hoek, 2005; Bulling and Dastani, 2011]. In this chapter we investigate how the behavior of agents in NORMASs can be controlled and coordinated by means of formal and game theoretical methods.

In Section 3.1 we propose an approach based on mechanism design and social choice theory [Shoham and Leyton-Brown, 2009; Osborne and Rubinstein, 1994] to analyze whether a given set of norms is sufficient to influence the agents’ behaviors in such a way that a desirable system behavior emerges. Often, sanctioning mechanisms need to be installed to handle norm violations. However, before norm violations can be sanctioned they have to be detected. If there

is a law prohibiting over-speeding, but there are no speed cameras, the law will probably have little effect. Hence, it is necessary to have an efficient monitor infrastructure that allows to observe the system and detect norm violations. This is the subject of Section 3.2. We propose a formal, logic-based model of monitors and analyze its properties.

Finally, we consider the aspect of responsibility. If norm violations or any kind of (mis)behavior is detected it is necessary to determine the agents that are responsible for it, in order to take appropriate measures including the sanctioning of norm violating agents. Especially in the setting of joint/simultaneous actions this is a challenging task and relates to collective responsibility [Smiley, 2011; Grossi et al., 2007; Bulling and Dastani, 2013]. We address this problem in Section 3.3 where we propose a formal modelling of responsibility in a strategic context.

3.1 Verifying Normative Behavior via Normative Mechanism Design

This section summarizes:

Bulling, N. and Dastani, M. (2011). Verification and implementation of normative behaviours in multi-agent systems. In *IJCAI 2011, Proceedings of the 22nd International Joint Conference on Artificial Intelligence, Barcelona, Catalonia, Spain, July 16-22, 2011*, pages 103–108, Barcelona, Spain. IJCAI/AAAI

MASs are designed for specific purposes and the emerging system behavior should meet those. However, as agents are autonomous and self interested they do not necessarily care about the system objective. Even if they cared there often would be a need for the coordination of action execution/selection in order to obtain a desirable behavior. In this work we analyze how to influence the behavior of self-interested agents in such a way that the system specification is actually met. We follow a normative approach. As said above, norms have already been proven suitable to change/control agents' behavior [Dastani et al., 2009a,b; Esteva et al., 2004; Jones and Sergot, 1993], in particular also using logical approaches [Ågotnes and Wooldridge, 2010; Ågotnes et al., 2007]. The work is also motivated by the rule-based Organisation Oriented Programming Language (2OPL) which allows to implement normative environments using norms and sanctioning mechanisms [Dastani et al., 2009a,b].

Given this practical context our modeling starts from a set of action specifications and an initial state. If successively applied the action specifications generate a CGS as discussed in Section 2. To model a MAS, we additionally assume that agents have goals and preferences. This is modeled by LTL-formulae. More precisely, an agent has a list of LTL-formulae each of which is associated a utility value. These formulae induce a utility value for each path in the model. The path is assigned the highest value of those formulae satisfied in the list. As complete strategy profiles yield a unique path in the model, a utility value can be assigned to each strategy profile. Rational agents try to maximize their payoffs and act accordingly. This can be formalized by defining a strategic game from a given CGS extended with goals of agents. The construction is similar to the transformation of an extensive form game to a strategic game, well-known from the game theory literature. We simply enumerate all strategy profiles in the CGS and evaluated LTL-formulae to compute the payoff of each agent for a given strategy profile. As a consequence, the game theoretical machinery can be applied to our setting.

In this paper, we are concerned with how the behavior of agents can be influenced/coordinated such that the outcome of their acting is aligned with the objective of the system. Per se, the agents try to find the best strategy with respect to their individual goals; they care little, if at all, about other agents' goals or the system objective. To investigate this problem we use ideas from mechanism design and social choice theory [Osborne and Rubinstein, 1994; Shoham

and Leyton-Brown, 2009]. An overview of the setting is given in Figure 3.1. First, we define

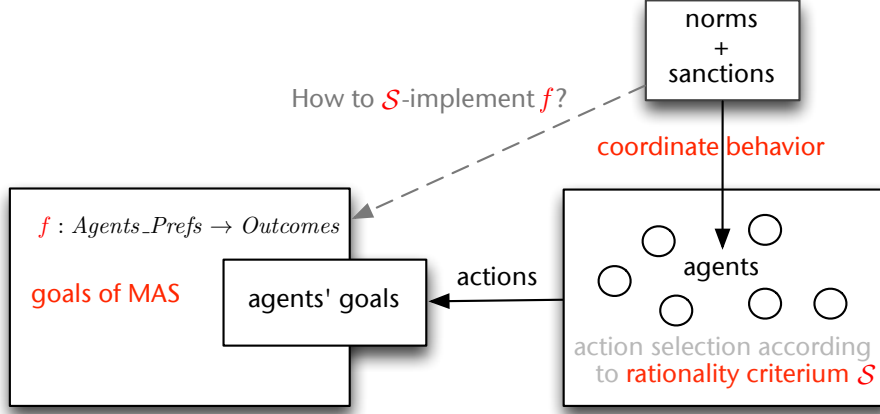


Fig. 3.1. Overview of normative mechanism design.

a normative behavior function f as a function $f : Prefs \rightarrow LTL$ to specify the desired system objective $f(\gamma_1, \dots, \gamma_k)$ for a given vector of preferences of the agents, containing a preference list γ_i for each agent i . That is, depending on the agents' preferences the system designer specifies the desired system property by means of an LTL-formula. Note that the system designer is not forced to take the agents' preferences into account. Just as well, the system designer could define f as a constant function. Often, however, the system designer is not aware of the specific objectives of an agent such that a social choice function can be used to ensure that the outcome is desirable with respect to all possible preferences. Second, we assume that agents act rationally according to some game theoretical solution concept \mathcal{S} , and compute the equilibria according to the preferences $\gamma_1, \dots, \gamma_k$ in the associated strategic game obtained from the CGS and the preferences as explained above. Third, we check whether the equilibria satisfy $f(\gamma_1, \dots, \gamma_k)$. If this is the case, we are in a good position: if the agents act rationally and an appropriate equilibrium is chosen the system outcome will satisfy the system specification.

Interesting is the case when not all equilibria satisfy the system objective. We propose *normative mechanism design* as a formal tool to investigate the effect of norms and sanctions to influence the agents behavior. A normative mechanism M is essentially a set of norms and sanctions. The violation of a norm can be sanctioned by modifying the structure of the CGS. If the modification is successful and the resulting equilibria agree with the system outcome specified by f , we say that M implements f wrt. the solution concept \mathcal{S} . The sanctioning rules essentially correspond to a relabelling of states, or a modification of the underlying transition structure as action specifications are defined in terms of pre- and postconditions. For example, if an agent has the goal of avoiding paying a fine, which can be specified by $\mathbf{G}\neg\text{fine}$, imposing a sanction of paying a fine to some state will provide an incentive to the agent to avoid this very state in which it would have to pay a fine. As a consequence, the behavior of the agent may change.

In addition to the formal modeling framework, we analyse decision problems related to the question whether the system behavior can be modified in such a way that the system objective

is satisfied. For our results we assume the concept of Nash equilibrium. In summary, the main contributions are:

- We propose normative mechanism design to systematically study the effects of imposing norms and sanctions on a MAS.
- We show that the verification problem, i.e. whether a specific set of norms does ensure a desired system behavior, is **coNP**-complete.
- We show that the existence problem of an appropriate set of norms is Σ_3^P -complete.

3.2 Monitoring Norm Violations in Multi-Agent Systems

This section summarizes:

Bulling, N., Dastani, M., and Knobbout, M. (2013a). Monitoring norm violations in multi-agent systems. In *Proc. of the 12th Int. Conf. on Autonomous Agents and Multi-Agent Systems (AAMAS 2013)*, pages 491–498, Saint Paul, Minnesota, USA. IFAAMAS, ACM Press

In the previous section we have proposed normative mechanism design as a means to control MASs. Sanctioning mechanisms were used to punish misbehaving agents in order to change/influence their behavior. The issue of how to detect the violation of norms, however, was not discussed. But of course, before sanctions can be imposed the violation of norms must be detected. Detecting norm violations is difficult as monitoring mechanisms are often not perfect, due to cost or resource constraints, or due to technological limitations. In this paper, we propose a formal, logic-based setting of norm monitoring and norm violation detection. We analyse formal properties of monitors, in particular whether monitors are sufficient to detect all violations with respect to a given norm or whether such a monitor can be obtained by combining existing ones.

In the following we describe the basic model of the underlying normative framework. We model it as a Kripke structure \mathcal{J} ; we abstract from the specific agents and consider only temporal transitions. We use $\mathcal{R}_{\mathcal{J}}$ or just \mathcal{R} to denote the set of runs/paths in the Kripke structure, i.e. \mathcal{R} is a set of infinite sequences of interconnected states. From an abstract point of view a *norm* is simply a subset of runs $\mathcal{N} \subseteq \mathcal{R}$. It classifies runs into “good” and “bad” ones. A *monitor* observes the behavior of the system. Ideally, if the current behavior is modeled by run r the monitor should observe r . Often however, a monitor is not perfect and may not be able to perfectly identify the current run. Therefore, we model a monitor as a function $m : \mathcal{R} \rightarrow \mathcal{P}(\mathcal{R})$. $m(r)$ is the set of runs, m considers possible if the true/current run is r . It can be the case that $r \in m(r)$, but just as well that $r \notin m(r)$. In the latter case, the monitor does not consider the true run r possible. We define several characteristics of monitors. Before we relate monitors and norms we describe how to use LTL-formulae to define norms. For an LTL-formula χ , a χ -norm is defined as the set $\mathcal{N}_{\chi} = \{r \in \mathcal{R} \mid r \models \chi\}$. That is, \mathcal{N}_{χ} describes the normative behavior as the set of runs that satisfy χ . Now, we can define what it means for a monitor to detect, or to not detect a violation of a norm. For example, we say that monitor m returns on input run r

- χ -violation iff $\mathcal{J}, m(r) \models \neg\chi$; and
- χ -compliance iff $\mathcal{J}, m(r) \models \chi$

where for a set $X \subseteq \mathcal{R}$ of runs we define $\mathcal{J}, X \models \varphi$ iff $\mathcal{J}, r \models_{\text{LTL}} \varphi$ for all $r \in X$. A χ -violation of norm χ is detected wrt. run r , if on all behaviors that the monitor considers possible, $\neg\chi$ holds. This does not mean that a real violation has occurred, a monitor can make mistakes in both

ways: it can detect a violation when no violation occurred; and just as well may not detect a violation in case an actual violation occurred. Next, it is outlined what it means for a monitor to be sound, complete and sufficient: m is

- χ -*sound* in \mathcal{J} iff for all $r \in \mathcal{R}$ it holds: $\mathcal{J}, m(r) \models \neg\chi$ implies $\mathcal{J}, r \models \neg\chi$. In words, a monitor is sound with respect to a norm χ when for every possible run of the system, it holds that whenever a χ -violation is detected it is the case that the run was a χ -violation.
- χ -*complete* in \mathcal{J} iff for all $r \in \mathcal{R}$ it holds: $\mathcal{J}, r \models \neg\chi$ implies $\mathcal{J}, m(r) \models \neg\chi$. In words, a monitor is complete with respect to a norm χ when for every possible run of the system, it holds that whenever the run causes a χ -violation it is the case that a χ -violation is detected.
- χ -*sufficient* in \mathcal{J} if m is χ -sound and χ -complete.

Ideally, we are interested in sufficient monitors as they detect all “relevant” norm violations and only those. Up to this moment, the notion of monitor is rather abstract, for each norm there exists a sufficient monitor. In the following the definition of monitor is made more concrete. We use LTL-formulae to define monitors. For an LTL-formula ξ we define a ξ -monitor m_ξ by

$$m_\xi(r) := \{r' \in \mathcal{R} \mid \mathcal{J}, r \models \xi \text{ iff } \mathcal{J}, r' \models \xi\}.$$

Such a monitor defines an equivalence relation on the set of runs; the relation has at most two equivalence classes. The notion of norm and monitor are specified using computational methods. This makes it possible to devise decision procedures to determine whether a given monitor is sufficient for a given norm. Therefore, we present characterization results. One of the characterizations expresses that m_ξ is χ -sufficient in \mathcal{J} if, and only if, $\mathcal{J} \models \neg\chi$ or $\mathcal{J} \models \chi$ or $\mathcal{J} \models \neg\xi \leftrightarrow \chi$ or $\mathcal{J} \models \xi \leftrightarrow \chi$. Thus, if χ is not a trivial formula, then χ must be equivalent to ξ or $\neg\xi$. This result for “simple” LTL-monitors is only a corollary of a more sophisticated characterization result for more expressive monitors.

By operator \oplus two or more LTL-monitors can be combined to a new monitor which is not necessarily expressible by an LTL-monitor. The formal definition of \oplus looks rather simple, for two monitors m and m' , we define

$$m \oplus m' : \mathcal{R} \rightarrow \mathcal{P}(\mathcal{R}) \text{ with } m \oplus m'(r) := m(r) \cap m'(r).$$

In particular, $m \oplus m'$ is no longer a binary classifier but can have more than two equivalence classes. We also present a characterization theorem for combined LTL-monitors. There can be several reasons to combine monitors from simpler ones. For example, the set of available monitors is fixed, or only specific (simple) LTL-formulae can be used. Now, the characterization theorems help to solve interesting decision problems about monitors. For example, we can pose the following questions:

1. Does there exist an LTL-monitor m_ξ which is χ -sufficient over \mathcal{J} ?
2. Is a given monitor m (pure LTL-based or combined) χ -sufficient over \mathcal{J} ?
3. Is there a monitor in M , where M is a set of monitors, which is χ -sufficient over \mathcal{J} ?
4. Can we combine monitors $m_1, \dots, m_k \in M$ in such a way that $m_1 \oplus \dots \oplus m_k$ is χ -sufficient?

In the paper we show that all these problems are **PSPACE**-complete. In summary, the main contributions of the paper are:

- We propose a formal framework for monitoring norm violations and a special class of monitors based on LTL-formulae.
- We give characterization results for the existence of appropriate LTL-based monitors.
- We show that the problem whether a given LTL-based monitor is sufficient for detecting norm violations is **PSPACE**-complete. An analogous questions wrt. to the combination of LTL-monitors has the same complexity.

3.3 Coalitional Responsibility in Strategic Settings

This section summarizes:

Bulling, N. and Dastani, M. (2013). Coalitional responsibility in strategic settings. In Leite, J. and Son, T. C., editors, *14th Int. Workshop on Computational Logic in Multi-Agent Systems (CLIMA XIV)*, LNCS, pages 172–189, Corunna, Spain. Springer

In the two previous sections we have proposed formal approaches to analyze the effect of norms to influence agents’ decision making in MASs, and to construct monitors for detecting norm violations. The proposed monitors detect norm violations from a systemic perspective, not necessarily, however, *which* agent was responsible for a norm violation. Monitors detect events and not necessarily actions of agents. Also, in the case of simultaneous actions, all agents contributed to an action which makes it difficult to ascribe responsibility to individuals or even groups of agents. It is a non-trivial and highly relevant problem to determine which agent or group of agents can be held responsible for a specific outcome. In this work, we propose a formal and abstract notion of responsibility which is based on strategic power. It does not involve any moral connotation per se. Furthermore, our analysis allows to assign degrees of responsibility to sub-groups of agents in order to analyze which groups can be considered “more responsible than others”. This is especially appealing in an organizational context.

In the following we briefly review the formal setting. First, we define a state of affairs as a non-empty set of states. A coalition C is said to be responsible for a state of affairs if C is the smallest coalition that can prevent the state of affairs. Prevention means that the coalition C can guarantee that the system will not be in any of the states of the state of affairs. Using ATL^* , this can be specified as $\langle\langle C \rangle\rangle \mathbf{X} \neg \varphi$ where φ describes the state of affairs. This is a rather strong notion of responsibility as there may be several, incomparable coalitions that can prevent a state of affairs, and thus, no smallest one. For this reason, the definition is relaxed. A weakly responsible coalition for a state of affairs is a *minimal* coalition C that can prevent the state of affairs. Now, there can be several weakly responsible coalitions. The underlying intuition is that if the state of affairs has obtained, then none of the weakly responsible coalitions acted in a way to prevent the state of affairs from obtaining. They are all somewhat responsible. To illustrate this, we consider the CGS shown in Figure 3.2. We refer to player 1 as “Producer 1”, to 2 as

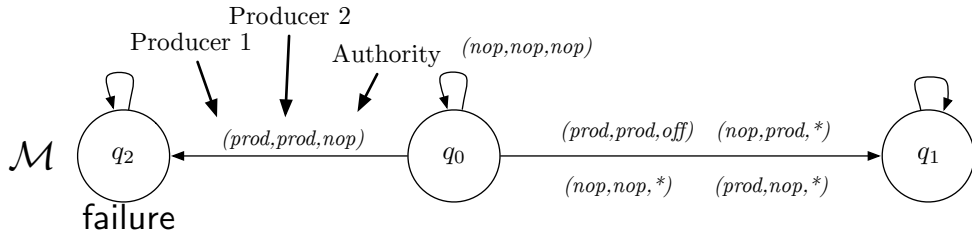


Fig. 3.2. The CGS $\mathfrak{M}_1 = (\{1, 2, 3\}, \{q_0, q_1, q_2\}, \{prod, nop, off\}, d, o)$ where $d_1(q_0) = d_2(q_0) = \{prod, prod\}$, $d_3(q_0) = \{off, prod\}$ and $d_i(q) = \{prod\}$ for all $i \in \{1, 2, 3\}$ and $q \in \{q_1, q_2\}$. The outcome function o is shown in the figure, e.g. $o(q_0, (drive, drive, prod)) = q_2$. The star \star represents any available action, i.e. $\star \in \{prod, off\}$.

“Producer 2”, and to 3 as “Authority”. Moreover, we assume that q_0 is the initial state subject

to which we evaluate the responsibility of coalitions. The story is as follows. Two electricity producers inject energy into the power grid. The production of renewable energy often depends on external circumstances, like wind strength and sun intensity. Very hot and windy days, e.g., can yield energy overproductions and even cause power failures. In our example we assume that both power producers can decide to produce power (or not). Moreover, a regulation authority can at all times force the producers to separate from the power grid. Let us assume that it is one of these windy days. If both producers decide to produce energy this will cause a power failure, if the regulation authority does not force the producers to stop their production. In this example the weakly responsible coalitions for $\{q_2\}$ are exactly $\{1\}$, $\{2\}$, and $\{3\}$. However, no coalition is responsible for $\{q_2\}$. Again, it is important to note that this does not mean that no coalition is responsible in the colloquial sense but simply that there are three (weakly) responsible coalitions. The authority who has not separated the producers from the grid is as responsible for a power failure (i.e. state $\{q_2\}$) as the producers themselves.

Now, we are interested in the question whether some coalitions can be considered “more responsible” than others. Therefore, we introduce the concept of crucial and necessary coalition. Crucial coalitions are subcoalitions of a (weakly) responsible coalition which cannot be replaced by other coalitions without the new coalition losing its characteristic of being (weakly) responsible. Necessary coalitions are defined similarly to crucial ones but the requirement of minimality of the newly formed coalition, included in the notion of weak responsibility is removed. In the example above, the only crucial coalition of any weakly responsible coalition is the empty set. For example, Producer 1 in the weakly responsible coalition $\{1\}$ can be replaced by Producer 2 yielding the weakly responsible coalition $\{2\}$. Intuitively, this means that all members of a weakly responsible coalition are “equally responsible” within this coalition. In the paper, we investigate properties of these types of coalitions and in particular show that the maximally necessary coalition is unique and corresponds to the intersection of all weakly responsible coalitions.

In addition to the conceptual modeling and the characterization results we discuss how responsibility can be refined if the actions of some players have been observed. Finally, we also use a syntactic extension of Coalition Logic, essentially based on [Ågotnes et al., 2008], to give a purely logical characterization of our notion of responsibility. This shows that our notions of responsibility are purely based on strategic ability. The logical characterization also provides, in principle, an automatic way to reason about responsibility. In summary, the main contributions are:

- We propose a strategic notion of group responsibility.
- We introduce a degree of responsibility among groups of agents.
- We give a logical characterization (essentially by using (Quantified) Coalition Logic [Ågotnes et al., 2008; Pauly, 2002]) of responsibility which allows to reason about these concepts. Moreover, it shows that our notion of responsibility is purely strategic.

Analysing Multi-Agent Decision Making

Game theory [Osborne and Rubinstein, 1994] is a mathematical tool to model and analyze strategic interactions among rational players. A *strategic game* is a tuple $G = (\text{Agt}, (\text{Act}_i)_{i \in \text{Agt}}, \text{Out}, \text{out}, \mathbf{ut})$ composed of a set of agents $\text{Agt} = \{1, \dots, k\}$, a non-empty sets of actions¹ Act_i , one per agent $i \in \text{Agt}$, a set of outcomes Out , a mapping $\text{out} : \text{Act} \rightarrow \text{Out}$ from the set of action profiles $\text{Act} = \text{Act}_1 \times \dots \times \text{Act}_k$ to outcomes, and a vector of utility functions $\mathbf{ut} = (\text{ut}_1, \dots, \text{ut}_k)$, one utility function $\text{ut}_i : \text{Out} \rightarrow \mathbb{R}$ per agent. The utility functions model agents' preferences over outcomes. For each agent $i \in \text{Agt}$, we also define a preference relation \succeq_i over action profiles $\alpha, \alpha' \in \text{Act}$ as follows: $\alpha \succeq_i \alpha'$ iff $\text{ut}_i(\text{out}(\alpha)) \geq \text{ut}_i(\text{out}(\alpha'))$. We use the following example, taken from [Bulling, 2014b, Examples 1-3], to illustrate game theoretical reasoning:

Alice (A) has ordered a book and is waiting for delivery. Unfortunately, she does not remember whether she declared her home or office address. She has to decide now where to wait for the package: at home (action α_h) or at the office (action α_o). Unfortunately in addition to that, the address on the package is not well readable except for Alice's name. However, postman Bob (B), who has delivered Alice's packages for many years, knows both addresses of Alice. There are four possible outcomes of the interaction: $\text{Out} = \{HO, OO, OH, HH\}$. Outcome HO encodes that Alice is at home (by Alice executing action α_h) and the package was delivered to the office (by Bob executing action α_o); the other outcomes are interpreted analogously. Suppose Bob does not care too much whether Alice gets her package or not; mostly, he is interested to deliver the package as quickly as possible. As Alice's home is on Bob's way he prefers to deliver the package there; if Alice would be there too, all the better. Bob's utility function is specified by: $\text{ut}_B(HH) = 4$, $\text{ut}_B(OH) = 3$ and $\text{ut}_B(OO) = \text{ut}_B(HO) = 0$. The associated strategic game is given by $(\{A, B\}, (\{\alpha_o, \alpha_h\}, \{\alpha_o, \alpha_h\}), \text{Out}, (\text{ut}_A, \text{ut}_B))$ and shown in Figure 4.1(a). It is crucial to observe that Bob's decision influences Alice's. The action profile (α_h, α_h) yielding outcome HH is the unique *stable* solution: for all other action profiles one of the players would be better off to change her/his action. Suppose now, Bob still prefers to go to Alice's home but, as he is a nice guy, primarily prefers that Alice will receive her package: $\text{ut}_B(HH) = 4$, $\text{ut}_B(OO) = 3$, $\text{ut}_B(OH) = 2$, $\text{ut}_B(HO) = 1$. This new setting is depicted in Figure 4.1(b). Where should Alice and Bob go now? When analyzing the game it is important that Alice and Bob cannot communicate with each other nor make binding agreements. The modified game has two stable action profiles: (α_o, α_o) and (α_h, α_h) with the associated outcomes OO

¹ In this context, actions are also called strategies.

A\B	α_o	α_h	A\B	α_o	α_h
α_o	(4, 0)	(2, 3)	α_o	(4, 3)	(2, 2)
α_h	(1, 0)	(3, 4)	α_h	(1, 1)	(3, 4)

Fig. 4.1. Package deliver example. On the left (a) with selfish Bob and right (b) with cooperative Bob.

and HH , respectively. From none of these action profiles a player can unilaterally deviate from his/her action to obtain a better utility. How to coordinate to reach one of these outcome is another problem.

The action profiles yielding the stable outcomes OO and HH in the example are called *Nash equilibria*. In general, an action profile $\alpha \in \text{Act}$ is a *Nash equilibrium* [Nash, 1950] if no agent can unilaterally deviate to improve its outcome. Formally, $\alpha \in \text{Act}$ is a Nash equilibrium if, and only if, for all agents $i \in \text{Agt}$ and all actions $\alpha'_i \in \text{Act}_i$ of player i it is the case that $\alpha \succeq_i (\alpha_1, \dots, \alpha_{i-1}, \alpha'_i, \alpha_{i+1}, \dots, \alpha_k)$.

Game theory has its origins in economics. It is suitable to analyse the decision making of economically or politically driven stakeholders. In multi-agent systems game theory has become a popular tool to investigate the behavior of rational agents or system components. Game theory can also be applied to our smart grid example. The stakeholders (customers, power producers, regulation authorities, etc.) can be modeled as rational players all with their own interests and capabilities. To analyze strategic interactions and decision making in MASs we also use the rather abstract model of Boolean games. A *Boolean game* [Harrenstein et al., 2001; Bonzon et al., 2006; Dunne et al., 2008] is a computational, compact model of interactions in MASs. Agents control propositional variables; actions correspond to setting a variable true or false, respectively. The control of a variable is exclusive. Most importantly, Boolean games include qualitative objectives in form of propositional logic formulae. The truth of formulae usually depends on the actions of multiple agents. This requires strategic reasoning and acting. Suppose, for example, that player 1 has the objective $(p \wedge q) \vee (r \wedge s)$ where only p and r are controlled by 1. The variable q and s are controlled by agent 2 and 3, respectively. Then, agent 1 relies on 2 or 3 to satisfy its objective. So, it is a strategic decision whether 1 should set p or r true. In addition to the qualitative objective, the setting of truth values does not come for free and incurs some cost. Thus, as a secondary objective agents want to minimize costs. Boolean games allow to model many interesting aspects of strategic interactions in MASs. In this thesis we use Boolean games to model secrecy aspect in multi-agent decision making, and to analyze stability in socio-technical systems.

In Section 4.2, we give an overview of multi-agent decision making. Then, in Section 4.2 we use game theoretical concepts to analyze and to compute network topologies in mobile-ad hoc networks, and investigate properties related to optimality and stability.

In Section 4.3 we use Boolean games to analyze agents' decision making in case they have goals that they want to keep secret. That is, an agent tries to achieve its goal without letting others know what the goal is until it has actually been achieved. We model this by assuming that agents take their decisions sequentially. Hence, actions have to be selected in a clever way in order not to reveal the objectives.

Finally, in Section 4.4 we use Boolean games to analyze stable behaviors in socio-technical systems [Trist, 1981], which are systems combining a technical part (e.g. the physical infrastructure of a company) with a social one.

4.1 A Survey of Multi-Agent Decision Making

This section summarizes:
 Bulling, N. (2014b). A Survey of Multi-Agent Decision Making. *KI*, 28(3):147–158

In this article we give an overview of multi-agent decision making (MADM). Figure 4.2 illustrates the various aspects of MADM. We discuss classical decision making considering qualitative and

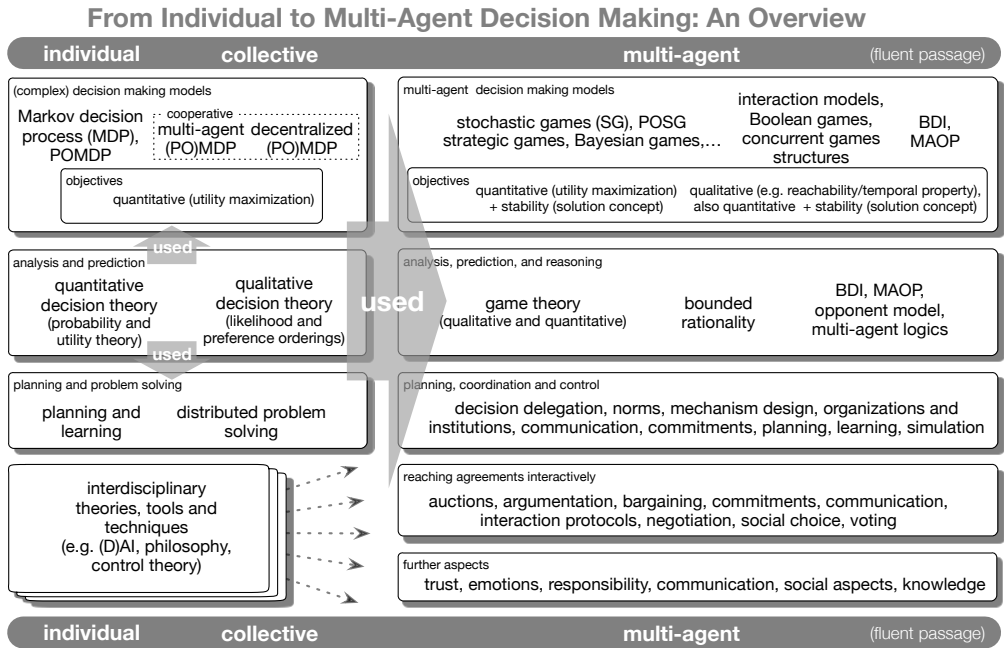


Fig. 4.2. Overview of aspects relevant to MADM. The passage from individual (left) to multi-agent (right) is partly fluent.

quantitative approaches. In classical quantitative decision theory the worth of an outcome is measured by a *utility function* $ut : Out \rightarrow \mathbb{R}$. An agent tries to maximize its expected utility. The quantitative approach is appealing if the complete model is given but has limitations in case of dynamic or unforeseen situations. The same holds if there is no easy way to assign utility values to outcomes. Qualitative decision theory replaces utility values with qualitative descriptions, e.g. by using relations or logic-based approaches. Then, we turn to game theory, *the* mathematical framework for analyzing MADM. A key characteristic of MADM is the self-interest of agents, and that their decisions affect the decisions of others and vice versa. That is, when computing the best action, agents have to take into consideration the behavior of other agents. This has been illustrated in the example given at the beginning of this section. In the survey article, we also discuss how decisions can be influenced and controlled using mechanism design. We also touch upon human decision making, the decision making of bounded rational agents, as well as on multi-agent programming and multi-agent logics. Then, we turn to the interactive

process of MADM in more detail. In this part we especially give an overview on negotiation and argumentation techniques. We also consider norms and organizations as means to control the decision making process in MASs.

4.2 A Game-Theoretic Approach to Stability in Mobile Ad-Hoc Networks

This section summarizes:

Bulling, N. and Popovici, M. (2014). A game-theoretic approach to compute stable topologies in mobile ad-hoc networks. *Journal of Logic and Computation*, 25(3):639–667

In this work we propose a formal modeling for analyzing and computing stable network topologies for inter-connecting users in mobile ad-hoc networks (MANETs). MANETs are networks in which mobile users can communicate in an ad-hoc way without relying on a fixed infrastructure. Examples of such networks include *delay-tolerant networks* [Fall, 2003], sensor networks and opportunistic networks [Pelusi et al., 2006; Lilien et al., 2007]. MANETs offer great possibilities for today’s demands, e.g. networks are created when they are needed; they can be used for many application domains; and they are easy to set-up among smart devices. But this flexibility also has a price when it comes to security as well as privacy issues [Djenouri et al., 2005; Hu and Perrig, 2004], and the quality of service and reliability of the network [Royer and Toh, 1999]. In particular in a social context, it is important to incentivize users to *offer* services and not just to use them. Classical examples are file sharing platforms. The aim of this paper is to analyze and to compute network topologies which are accepted by users, that is, which offer a “fair” solution. We take into consideration aspects related to fairness and stability and make use of game theoretical techniques. We also take into account user constraints about the network topology, e.g. users can specify routing constraints. A schematic view of the framework is shown in Figure 4.3.

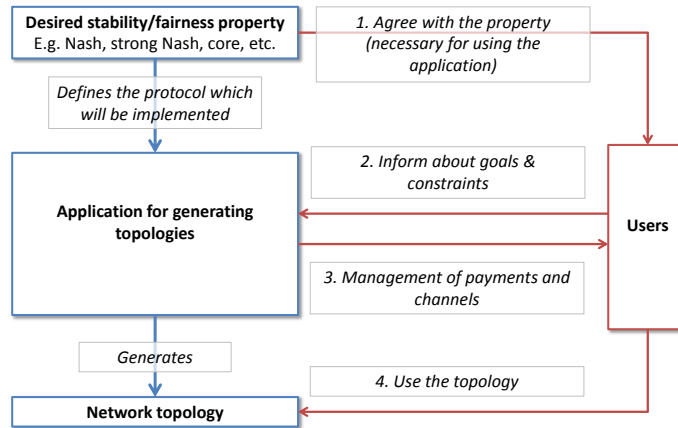


Fig. 4.3. The basic idea of the complete framework [Bulling and Popovici, 2014].

The basic model is called *network frame* $\mathcal{F} = (\text{Users}, N, \text{throughput}, \text{trans_cost}, \Pi, \mathcal{T})$ consisting of a set of users Users , a neighborhood function $N : \text{Users} \rightarrow 2^{\text{Users}}$ with $i \notin N(i)$, a throughput function $\text{throughput} : \text{Links}_{\mathcal{F}} \rightarrow \mathbb{N}$, a transmission cost function $\text{trans_cost} : \text{Links}_{\mathcal{F}} \rightarrow \mathbb{R}^+$ where

$\text{Links}_{\mathcal{F}} = \{(i, j) \mid i, j \in \text{Users}, j \in N(i)\}$ is the set of all potential communication links in \mathcal{F} , a set of propositional symbols Π that represent different user properties, and a valuation function $\mathcal{I} : \text{Users} \rightarrow 2^{\Pi}$ assigning a set of propositions to each user. An example of a network frame is given by \mathcal{F}_1 shown in the leftmost subfigure of Figure 4.4, where $\text{Users} = \{1, 2, 3, 4\}$, $N(1) = \{2\}$, $N(2) = \{3, 4\}$, $N(3) = N(4) = \emptyset$, $\Pi = \{p, q, r\}$, $\mathcal{I}(1) = \emptyset$, $\mathcal{I}(2) = \{q\}$, $\mathcal{I}(3) = \{p, r\}$ and $\mathcal{I}(4) = \{p\}$. The transmission costs and throughput are defined as follows: $\text{trans_cost}((1, 2)) = 1$, $\text{trans_cost}((2, 4)) = 0.5$, $\text{trans_cost}((2, 3)) = 2$, and $\text{throughput}(l) = |\text{Users}|$ for all $l \in \text{Links}_{\mathcal{F}_1}$. In \mathcal{F}_1 (shown in Figure 4.4) the labelled dashed arrows describe the potential communication links; the numbers represent the transmission costs of each of the respective communication links. The transmission cost function encodes how costly it is to establish (and use) a potential communication link between two players. The throughput function defines how much data can be sent via a link. Here, we assume that the throughput defines the number of players that can use a link. If a link is used for more than one player, costs are shared equally.

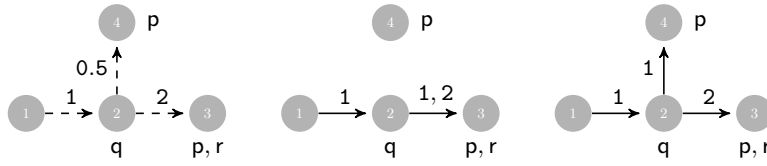


Fig. 4.4. A NF \mathcal{F}_1 (left) and two \mathcal{F}_1 -topologies \mathcal{T}_1 (middle) and \mathcal{T}_2 (right).

A network frame models only the *possible* communication links. A *network topology* over a network frame is a specific instantiation of the communication links. Two examples of topologies over \mathcal{F}_1 are \mathcal{T}_1 and \mathcal{T}_2 shown in the same figure. In \mathcal{T}_1 user 1 uses the channel from node 1 to 2, and both users share the channel from 2 to 3. Sharing a channel also means to share the incurred costs. Additionally, network frames are extended with user constraints/goals. Each player can specify a preference over network topologies, e.g. *network A should be accessible via at most two hops* or *Internet should be accessible via a path that doesn't pass through player i*, etc. Hence, the choice of a specific network topology depends on the cost of the topology and whether the constraints/goals are satisfied. In the example above, suppose player 1's goal is to reach a state in which p holds. Then, both topologies \mathcal{T}_1 and \mathcal{T}_2 satisfy this goal. In \mathcal{T}_1 the player uses the link (1, 2) and (2, 3), the latter jointly with player 2. In \mathcal{T}_2 it uses (1, 2) and (2, 4). Analogously, for player 2. The topology \mathcal{T}_2 incurs costs of 1.5 for player 1 where \mathcal{T}_1 incurs costs of $2 = 1 + \frac{2}{2}$. The latter denotes the costs of the channel from 2 to 3 for each player; the costs of 2 are shared among both players. Player 1 prefers topology \mathcal{T}_2 . On the other hand, player 2 favors \mathcal{T}_1 in case its goal was to visit a state in which r holds. In that topology the player has to pay 1 in comparison to costs of 2 in \mathcal{T}_2 . Also, \mathcal{T}_1 is globally optimal, the sum of the costs of all players is minimal. In this specific example, it can be argued that \mathcal{T}_1 is a stable topology. Player 1 prefers \mathcal{T}_2 but it cannot force player 2 to establish the link (2, 4)—each user decides which outgoing transition to establish, i.e. which messages to forward for which other users. Not using the link (2, 3), on the other hand, is also not an option for player 1 as its goals would not be satisfied.

In general, however, there may not be stable topologies. Also, stability depends on the very concept of stability used. The above reasoning corresponds to stability using the concept of Nash equilibrium. The next natural step is to consider the deviation of subgroups, the strong Nash equilibrium concept. Thus, the computation of “good” topologies should take into consideration aspects of (global) optimality, fairness, and stability. We investigate those aspects via a game theoretical modeling—non-cooperative as well as cooperative. We compute topologies based on

Nash as well as strong Nash equilibrium, and two variants of the core solution concept. The resulting topologies are compared to each other and are evaluated with respect to optimality, fairness, and stability. We show that the non-cooperative and cooperative solutions are different regarding the properties they induce and also from a conceptual point of view. Further, it is shown that non of the proposed solutions is completely satisfactory for stability and optimality, but that some—the cooperative ones, as we argue—solutions come quite close. In our opinion the specific choice of a solution concept depends on the considered scenario; in particular, whether the setting contains more cooperative or non-cooperative elements. We believe that it often makes sense to assume that players behave more cooperatively in the context of social applications.

In addition to the conceptual modeling and investigation of properties of the solution concepts, we also propose a computational setting based on the computation tree logic CTL [Clarke and Emerson, 1981]. The logic is used to specify the constraints/goals of a player about the topology. We analyze the complexity of decision problems and of the synthesis problem to actually compute topologies according to some solution concept. The main contributions of this work are:

- We propose a formal modeling to analyze network topologies in MANETs.
- We use game theoretical solution concepts to analyze aspects related to fairness, optimality and stability.
- We allow users to specify constraints, by means of CTL.
- We investigate computational complexity issues with respect to computing network topologies.

4.3 Reaching Your Goals Without Spilling The Beans: Boolean Secrecy Games

This section summarizes:

Bulling, N., Ghosh, S., and Verbrugge, R. (2013b). Reaching your goals without spilling the beans: Boolean secrecy games. In *PRIMA 2013: Principles and Practice of Multi-Agent Systems - 16th International Conference, Dunedin, New Zealand, December 1-6, 2013. Proceedings*, volume 8291 of *LNCS*, pages 37–53, Dunedin, New Zealand. Springer

Boolean games can be seen as strategic games extended with qualitative objectives in a computationally grounded setting. In these games, as in strategic games, agents act simultaneously and the agents' objectives are known to all other agents. In this work we assume that agents want to keep their objectives secret. More precisely, they want to keep the objectives secret until they will be achieved. We model this by assuming that agents act sequentially and observably to others. As a consequence, in order to keep an objective secret it is not enough to have a strategy to satisfy it, but at the same time to act in such a way that the other agents are uncertain about the agent's true objective. For example, suppose a company A would like to absorb a stock company B . It can be of strategic importance that the involved stock market players are not aware of A 's plan to buy sufficiently many stocks until A actually holds the majority of the stocks of B . This complicates the strategic reasoning process.

Our formal model uses the basic ingredients of Boolean games [Harrenstein et al., 2001; Bonzon et al., 2006], as discussed before. In particular, agents' objectives are given by propositional formulae and actions correspond to assigning truth values to propositional variables. We define a Boolean secrecy frame

$$F = (\text{Players}, II, (\mathcal{P}_i)_{i \in \text{Players}}, I, (I_i)_{i \in \text{Players}}, (C_i)_{i \in \text{Players}}, (C_i)_{i \in \text{Players}}),$$

where $\mathcal{P}layers$ and \mathcal{I} are non-empty sets of players and propositions, respectively; function $c_i : \Sigma_i \rightarrow \mathbb{R}^+$ represents the costs associated with the moves Σ_i (i.e. essentially two actions for each propositions controlled by player i : one to set it true and another one to set it false) of player i ; $C_i \in \mathbb{R}^+$ is the cost limit for player i ; $\mathcal{G} \subseteq \mathcal{L}$ is the set of possible goals for the players, which is commonly known to all players; and $\mathcal{G}_i \subseteq \mathcal{G}$ is the set of *secret goals* of player i , not visible to the other players.

In addition to standard Boolean games, players not only want one of their goals to become true, but to make a goal true without spilling the beans, meaning without others knowing about their goals until one goal has actually become true. Therefore, our model may be seen as a turn-based variant of Boolean games with additional assumptions. At each step one of the players decides about the truth of one of its variables. This action, however, may reveal information about the agents secret goals. In order to preserve secrecy of a player i , we require that at each step there is a non-goal formula φ' that could, however, be a potential goal of i from the other players' perspectives. Among other things, we require that φ' can be guaranteed by i at some possible (future) play. This already suggests that the order in which players move can affect who wins the game. Thus, a Boolean secrecy game is based on a Boolean secrecy frame together with a turn function defining which player is about to move next. Given such a Boolean secrecy game we are interested in the question whether there is a player which has a goal achieving strategy which incurs costs lower or equal to the players cost constraint. The notion of goal-achieving is rather sophisticated.

The conceptual modeling is the main contribution of the paper. We show that Boolean secrecy games are not determined, meaning there is not necessarily a winning player, and that the order in which players put forward their actions affects the outcome of the game. We also consider decision problems related to the question whether there is a winning player, and give computational complexity results. We show that this is a difficult problem: we prove Σ_2^P -hardness and membership in Σ_4^P for the most general problem. In summary, the main contributions are:

- We propose the framework of Boolean secrecy games.
- We analyze the complexity of determining whether there is a winning player. For a limited case we show that the problem is in \mathbf{P} if the game is given in explicit form. For the general case in which the order of interaction is known, we show that it is in Δ_2^P and \mathbf{coNP} -hard. Finally, we show that in the most general case, in which the order of interaction is unknown, the problem is in Σ_4^P and Σ_2^P -hard.

4.4 A Boolean Game Based Modelling of Socio-Technical Systems

This section summarizes:

Bulling, N. (2014a). A Boolean game based modelling of socio-technical systems. In Mueller, J. P., Weyrich, M., and Bazzan, A. L. C., editors, *MATES 2014: Multiagent System Technologies XII*, LNAI, pages 7–25. Springer

Social-technical systems (STSS) are complex systems in which social as well as technological aspects play a decisive role for their functioning. Social aspects are often related to people and their behavior, or societal constraints. The technical system captures the technology and processes not related to “societal issues”. Socio-technical theory is concerned with the *joint optimization* of both parts, that is, with the design of “good” systems comprising technological as well as social aspects. The connection of STSS with MASs is evident: both approaches contain self-interested actors, humans or intelligent agents, which need to cooperate with others in order

to bring about their tasks and the objective of the system. In this work we use techniques from MASs to model and to analyze STSs, and in particular, to investigate aspects related to system stability. We propose a formal model for the technical and social (sub)system of a STS. We model the social system by constrained Boolean games, a slight extension of Boolean games.

Formally, a *constrained Boolean game* is given by

$$\mathbf{G} = (\mathbf{Users}, \mathbf{II}, c, (\gamma_i)_{i \in \mathbf{Users}}, (\mathbf{II}_i)_{i \in \mathbf{Users}}, \varphi)$$

where $\mathbf{G}' = (\mathbf{Users}, \mathbf{II}, c, (\gamma_i)_{i \in \mathbf{Users}}, (\mathbf{II}_i)_{i \in \mathbf{Users}})$ is a Boolean game and $\varphi \in \text{PL}(\mathbf{II})$ is a propositional formula serving as (*global*) *constraint* on the agents' behavior. An assignment ξ is said to be φ -consistent iff φ follows from the assignment ξ , in the propositional sense. A global constraint can impose restrictions on the truth values of variables of the players and of the environment. In this paper, we are mainly interested in constrained Boolean games where φ is built over environmental variables only; that is, over variables controlled by no player. Such a constraint can be interpreted as information given to the players about the truth values of the environmental variables. We call these game Boolean games with information. They are similar to the variant of Boolean games considered in [Grant et al., 2014] where each player has a belief about the environmental variables. We define the Nash equilibrium solution concept for constrained Boolean games.

One of the key contributions of the paper is the use of Boolean games with information to model the distributed social subsystems of a socio-technical system. A socio-technical system consists of a technical system \mathcal{T} and a social system \mathcal{S} . The technical system is defined over a set of available objects or artefacts (e.g. offices), modeled by propositional variables, and a technical constraint T which models the size and structure of a socio-technical system. For example, T can encode the number of rooms in a building and their capacity. A social system is a tuple $\mathcal{S} = (\mathbf{Agt}, \mathbf{pow}, (S_1, \delta_1, \delta_1^I), \dots, (S_s, \delta_s, \delta_s^I), \iota)$ where \mathbf{Agt} is a set of agents, \mathbf{pow} specifies the power of agents or more precisely the power they are allowed to exercise in the social system (i.e. which variables they are allowed to control), and each S_i is a set of agents modeling an organization unit. Each organization unit has a private goal δ_i in form of a propositional formula. As this goal is not known to members outside the organization unit, each organization unit also publicly and truthfully announces parts of its private objective—the *public organization objective* δ_i^I . The public objective is used to coordinate the behaviors between the distributed organization units to achieve a desirable system behavior. Finally, ι is an incentive scheme which can be installed by the owner of the STS to influence the behavior of agents in the social system. Incentives could for instance model bonuses, extra vacation days, or other benefits. Analogously, it would also be possible to consider taxation schemes instead, modeling taxes, fines, etc.

The emerging system behavior is defined as a combination of the behaviors in each organization unit, which in turn corresponds to stable behaviors of the Boolean games with information, induced by each organization unit in a social system. Confidentiality constraints and system specifications are introduced to describe desirable properties of the behaviors of socio-technical systems. A natural question is whether the agents' behavior can be influenced in such a way that a given confidentiality constraint and system specification are met. The modeling as Boolean game (with information) has the advantage that we can use techniques known from the Boolean games literature. In particular, we analyze how incentive engineering [Wooldridge et al., 2013] can be used to influence the behavior in a social system to obtain a desirable system behavior. In the paper we give first logic-based characterization results, using techniques from [Wooldridge et al., 2013], which allow to answer such questions by a reduction to the satisfiability problem of quantified Boolean formulae. The main contributions of the paper are:

- A formal model of STSs.

- An approach combining the area of STSs with foundation of MASs (Boolean games).
- A proposal on how to “distribute” Boolean games in order to model social subsystems of a STS and to achieve stability.
- Logic-based characterization results for the existence of incentive schemes to stabilize STSs.

Conclusions

Multi-agent systems (MASs) are distributed (computer) systems composed of autonomously (inter-)acting system components referred to as *agents*. MASs offer a flexible framework to model and analyse many real world settings in which cooperation, self-interest, and autonomy are crucial elements. A key challenge in such settings is the control and coordination of behavior. However, due to the agents' autonomy behavior can often not be controlled, but at best be influenced in some way or another. For example, agents can be given incentives in order to affect their decision-making in such a way that the emergent behavior of all actors is desirable from the system's perspective. Such an approach can be successful if the incentives are sufficient to align the agents' behavior, primarily driven by their individual preferences, with the system's objectives. The properties of self-interest and autonomy make it challenging to find appropriate control mechanisms. Existing coordination and control approaches from the distributed system literature are often not applicable due to the lack of direct control on the system components of MASs. New methods and tools are needed. In this thesis formal foundations related to the subjects of decision making, coordination and control in MASs were proposed and investigated. In particular, the work in the thesis contributed to the following aspects: (i) logics for modelling and reasoning about the decision making of agents; (ii) influencing, controlling and coordinating decisions; and (iii) analyzing and predicting decisions.

In (i) we investigated (extensions of) temporal and strategic logics which capture specific capabilities of agents that influence their decision making. We gave an overview of models of strategic reasoning [Bulling et al., 2015] and analyzed how memory and information affect capabilities of agents in game-like settings [Bulling and Jamroga, 2014]. Limitations of existing memory-based semantics for the strategic logic ATL^* [Alur et al., 2002] were pointed out and a new "no forgetting semantics" for agents with truly perfect recall was presented [Bulling et al., 2014]. We also argued for the need of quantitative aspects in strategic logics and proposed *Quantitative ATL^** [Bulling and Goranko, 2013], an extension of ATL^* combining qualitative and quantitative reasoning. Then, in [Bulling and Jamroga, 2011], we took on a more computational point of view and proposed an epistemic extension of Alur et al. [2002]'s alternating μ -calculus that offers a new type of strategic ability as well as a promising computational complexity result regarding the model checking of epistemic strategic logics. In the last part of Section 2, we analyzed logic-based settings of fragments of BDI-based temporal logics with respect to their computational complexity [Bulling and Hindriks, 2011]. The logics discussed in this work allow to reason about agents' abilities. In particular, they can be used for specifications which can then serve as a basis for formal system verification.

If it appears (e.g. by using model checking) that agents are capable of producing undesirable system executions, the designer of the system can impose mechanisms to influence the agents' decision making in order to avoid such executions. This was the subject of part (ii) of the thesis. We merged mechanism design with normative systems [Bulling and Dastani, 2011] and analyzed whether the system designer can create a set of norms which is sufficient to influence the agents behavior in a way desirable for the system. We argued that this is just one piece of the whole process. Norm violations have to be detected and managed. Therefore, we investigated *monitors* to detect specific (undesirable) behaviors [Bulling et al., 2013a] and also how to ascribe *responsibility* to (groups of) agents [Bulling and Dastani, 2013].

In the last part of the thesis, we were concerned with analyzing the decision making process of agents under aspects of stability, privacy, and secrecy. First, we gave an overview on multi-agent decision making [Bulling, 2014b]. Then, we proposed a framework that *uses* game-theoretical solution concepts as protocols to analyze and to compute “fair” network topologies in mobile ad hoc networks [Bulling and Popovici, 2014]. We also modeled and investigated how secrecy/privacy issues affect decision making, using the Boolean game model [Bulling et al., 2013b]. Finally, in [Bulling, 2014a] we showed how Boolean games can be used as an abstract approach to model stability in socio-technical systems, taking into consideration confidentiality aspects.

Such formal approaches and tools to analyse and control autonomous systems are crucial for the development of reliable systems and will become even more crucial in the near future. Already today, existing technology is advanced and allows ubiquitous computing, for example, social applications are ever increasing and the activities in the daily life become strongly connected as in smart grids and smart homes. MASs provide a suitable abstraction of many types of complex systems. The formal methods investigated in this thesis can help to design and analyze these systems; for example, logics and model checking for system verification, norms to coordinate and control the behavior of users, and game theory to predict and better understand the complex and emerging system interactions. The work of this thesis contributes to the formal foundations of MASs. For future work it is interesting to apply the theories to tackle real world problems. This requires methods with good computational properties and empirical studies, e.g. by simulations. This also connects to another important aspect often neglected in a game theoretic setting: human behavior. There is an ever-increasing interplay between intelligent systems and humans and this must also be reflected in the formal tools used to analyse and develop these systems. In this context, simulation can also be used to provide a model of human behavior, and on a more foundational side it seems appealing to combine theories on bounded rationality and evolutionary game theory with existing formal methods to obtain suitable prediction methods. The area of interaction and decision making in complex, autonomous systems remains an interesting one and offers many future challenges.

References

- Adomavicius, G. and Tuzhilin, A. (2005). Toward the next generation of recommender systems: A survey of the state-of-the-art and possible extensions. *Knowledge and Data Engineering, IEEE Transactions on*, 17(6):734–749.
- Ågotnes, T. (2004). A note on syntactic characterization of incomplete information in atel. In *Proceedings of the Workshop on Knowledge and Games, Liverpool*, pages 34–42.
- Ågotnes, T. (2006). Action and knowledge in alternating-time temporal logic. *Synthese*, 149(2):377–409. Section on Knowledge, Rationality and Action.
- Ågotnes, T., van der Hoek, W., Tennenholtz, M., and Wooldridge, M. (2009). Power in normative systems. In *Proceedings of The 8th International Conference on Autonomous Agents and Multiagent Systems (AAMAS '09)*, pages 145–152, Richland, SC. IFAAMAS.
- Ågotnes, T., van der Hoek, W., and Wooldridge, M. (2007). Normative system games. In *Proceedings of the 6th International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS '07)*, pages 1–8, New York, NY, USA. ACM.
- Ågotnes, T., van der Hoek, W., and Wooldridge, M. (2008). Quantified coalition logic. *Synthese*, 165(2):269–294.
- Ågotnes, T. and Wooldridge, M. (2010). Optimal social laws. In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems: volume 1 - Volume 1, AAMAS '10*, pages 667–674, Richland, SC. International Foundation for Autonomous Agents and Multiagent Systems.
- Alechina, N., Logan, B., Nga, N. H., and Rakib, A. (2011). Logic for coalitions with bounded resources. *J. Log. Comput.*, 21(6):907–937.
- Alur, R., Henzinger, T. A., and Kupferman, O. (1997). Alternating-time Temporal Logic. In *Proceedings of the 38th Annual Symposium on Foundations of Computer Science (FOCS)*, pages 100–109. IEEE Computer Society Press.
- Alur, R., Henzinger, T. A., and Kupferman, O. (1998). Alternating-time Temporal Logic. *Lecture Notes in Computer Science*, 1536:23–60.
- Alur, R., Henzinger, T. A., and Kupferman, O. (2002). Alternating-time Temporal Logic. *Journal of the ACM*, 49:672–713.
- Andrighetto, G., Governatori, G., Noriega, P., and van der Torre, L. W. N., editors (2013). *Normative Multi-Agent Systems*, volume 4 of *Dagstuhl Follow-Ups*. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik.
- Baier, C. and Katoen, J.-P. (2008). *Principles of Model Checking*. The MIT Press.
- Blackburn, P., de Rijke, M., and Venema, Y. (2001a). *Modal Logic*. Number 53 in Cambridge Tracts in Theoretical Computer Science. Cambridge University Press, Cambridge, UK.

- Blackburn, P., de Rijke, M., and Venema, Y. (2001b). *Modal Logic*. Cambridge University Press.
- Boella, G., Van Der Torre, L., and Verhagen, H. (2006). Introduction to normative multiagent systems. *Computational & Mathematical Organization Theory*, 12(2-3):71–79.
- Bohy, A., Bruyère, V., Filiot, E., and Raskin, J.-F. (2013). Synthesis from LTL specifications with mean-payoff objectives. In Piterman, N. and Smolka, S. A., editors, *TACAS*, volume 7795 of *Lecture Notes in Computer Science*, pages 169–184. Springer.
- Bonzon, E., Lagasque-Schiex, M.-C., Lang, J., and Zanuttini, B. (2006). Boolean games revisited. In *ECAI*, pages 265–269.
- Bulling, N. (2014a). A Boolean game based modelling of socio-technical systems. In Mueller, J. P., Weyrich, M., and Bazzan, A. L. C., editors, *MATES 2014: Multiagent System Technologies XII*, LNAI, pages 7–25. Springer.
- Bulling, N. (2014b). A Survey of Multi-Agent Decision Making. *KI*, 28(3):147–158.
- Bulling, N. and Dastani, M. (2011). Verification and implementation of normative behaviours in multi-agent systems. In *IJCAI 2011, Proceedings of the 22nd International Joint Conference on Artificial Intelligence, Barcelona, Catalonia, Spain, July 16-22, 2011*, pages 103–108, Barcelona, Spain. IJCAI/AAAI.
- Bulling, N. and Dastani, M. (2013). Coalitional responsibility in strategic settings. In Leite, J. and Son, T. C., editors, *14th Int. Workshop on Computational Logic in Multi-Agent Systems (CLIMA XIV)*, LNCS, pages 172–189, Corunna, Spain. Springer.
- Bulling, N., Dastani, M., and Knobbout, M. (2013a). Monitoring norm violations in multi-agent systems. In *Proc. of the 12th Int. Conf. on Autonomous Agents and Multi-Agent Systems (AAMAS 2013)*, pages 491–498, Saint Paul, Minnesota, USA. IFAAMAS, ACM Press.
- Bulling, N., Dix, J., and Jamroga, W. (2010). Model checking logics of strategic ability: Complexity. In Dastani, M., Hindriks, K. V., and Meyer, J.-J. C., editors, *Specification and Verification of Multi-Agent Systems*. Springer.
- Bulling, N. and Farwer, B. (2010). On the (Un-)Decidability of Model-Checking Resource-Bounded Agents. In Coelho, H. and Wooldridge, M., editors, *Proceedings of the 19th European Conference on Artificial Intelligence (ECAI 2010)*, pages 567–572, Lisbon, Portugal.
- Bulling, N., Ghosh, S., and Verbrugge, R. (2013b). Reaching your goals without spilling the beans: Boolean secrecy games. In *PRIMA 2013: Principles and Practice of Multi-Agent Systems - 16th International Conference, Dunedin, New Zealand, December 1-6, 2013. Proceedings*, volume 8291 of *LNCS*, pages 37–53, Dunedin, New Zealand. Springer.
- Bulling, N. and Goranko, V. (2013). How to be both rich and happy: Combining quantitative and qualitative strategic reasoning about multi-player games (extended abstract). In *Proc. of the 1st International Workshop on Strategic Reasoning*, EPTCS, pages 33–41, Rome, Italy.
- Bulling, N., Goranko, V., and Jamroga, W. (2015). Logics for Reasoning About Strategic Abilities in Multi-Player Games. In van Benthem, J., Ghosh, S., and Verbrugge, R., editors, *Models of Strategic Reasoning*, number 8972 in *LNCS*, pages 93–136. Springer.
- Bulling, N. and Hindriks, K. V. (2011). Taming the complexity of linear time BDI logics. In *Proceedings of the 10th International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2011)*, pages 275–282, Taipei, Taiwan. ACM Press.
- Bulling, N. and Jamroga, W. (2011). Alternating epistemic mu-calculus. In *IJCAI 2011, Proceedings of the 22nd International Joint Conference on Artificial Intelligence, Barcelona, Catalonia, Spain, July 16-22, 2011*, pages 109–114, Barcelona, Spain. IJCAI/AAAI.
- Bulling, N. and Jamroga, W. (2014). Comparing variants of strategic ability: how uncertainty and memory influence general properties of games. *Journal of Autonomous Agents and Multi-Agent Systems*, 28(3):474–518.
- Bulling, N., Jamroga, W., and Popovici, M. (2014). ATL* with truly perfect recall: Expressivity and validities. In *Proceedings of the 21st European Conference on Artificial Intelligence*

- (*ECAI 2014*), volume 263 of *Frontiers in Artificial Intelligence and Applications*, pages 177–182, Prague, Czech Republic. IOS Press.
- Bulling, N., Köster, M., and Popovici, M. (2012a). A game theoretic approach for optimal network topologies in opportunistic networks. In Fisher, M., van der Torre, L., Dastani, M., and Governatori, G., editors, *Computational Logic in Multi-Agent Systems - 13th International Workshop, CLIMA XIII, Montpellier, France, August 27-28, 2012. Proceedings*, volume 7486 of *Lecture Notes in Computer Science*, pages 128–145, Montpellier, France. Springer.
- Bulling, N., Köster, M., and Popovici, M. (2012b). A game theoretic approach for stable network topologies in opportunistic networks. Technical report, Clausthal University of Technology.
- Bulling, N. and Popovici, M. (2014). A game-theoretic approach to compute stable topologies in mobile ad-hoc networks. *Journal of Logic and Computation*, 25(3):639–667.
- Chatterjee, K., de Alfaro, L., and Henzinger, T. A. (2011). Qualitative concurrent parity games. *ACM Trans. Comput. Log.*, 12(4):28.
- Chatterjee, K. and Doyen, L. (2012). Energy parity games. *Theor. Comput. Sci.*, 458:49–60.
- Chatterjee, K. and Henzinger, T. A. (2012). A survey of stochastic ω -regular games. *J. Comput. Syst. Sci.*, 78(2):394–413.
- Chatterjee, K., Henzinger, T. A., and Jurdzinski, M. (2005). Mean-payoff parity games. In *Proc. of LICS'2005*, pages 178–187. IEEE Computer Society.
- Chopra, A. K. and Singh, M. P. (2013). Agent Communication. In Weiss, G., editor, *Multiagent Systems (second edition)*, chapter 3. MIT Press.
- Clarke, E. and Emerson, E. (1981). Design and synthesis of synchronization skeletons using branching time temporal logic. In *Proceedings of Logics of Programs Workshop*, volume 131 of *Lecture Notes in Computer Science*, pages 52–71.
- Clarke, E., Grumberg, O., and Peled, D. (1999). *Model Checking*. MIT Press.
- Cohen, P. R., Levesque, H. R., and Smith, I. (1997). On team formation. In Hintikka, J. and Tuomela, R., editors, *Contemporary Action Theory. Synthese*.
- Dastani, M., Grossi, D., Meyer, J.-J. C., and Tinnemeier, N. (2009a). Normative multi-agent programs and their logics. In *Proceedings of KRAMAS 2008*, volume LNAI 5605, pages 16–31. Springer.
- Dastani, M., Tinnemeier, N., and Meyer, J.-J. C. (2009b). A programming language for normative multi-agent systems. In Dignum, V., editor, *Multi-Agent Systems: Semantics and Dynamics of Organizational Models*. Information Science Reference.
- de Alfaro, L., Henzinger, T. A., and Kupferman, O. (2007). Concurrent reachability games. *Theor. Comput. Sci.*, 386(3):188–217.
- Della Monica, D., Napoli, M., and Parente, M. (2011). On a logic for coalitional games with priced-resource agents. *Electr. Notes Theor. Comput. Sci.*, 278:215–228.
- Demri, S. and Schnoebelen, P. (1997). The complexity of propositional linear temporal logics in simple cases. Technical report.
- Djenouri, D., Khelladi, L., and Badache, N. (2005). A survey of security issues in mobile ad hoc and sensor networks. *IEEE Communications Surveys and Tutorials*, 7(1-4):2–28.
- Dunin-Keplicz, B. and Verbrugge, R. (2006). Awareness as a vital ingredient of teamwork. In *Proceedings of the 5th international joint conference on Autonomous agents and multiagent systems*, pages 1017–1024.
- Dunne, P. E., van der Hoek, W., Kraus, S., and Wooldridge, M. (2008). Cooperative boolean games. In Padgham, L., Parkes, D. C., Müller, J. P., and Parsons, S., editors, *AAMAS (2)*, pages 1015–1022. IFAAMAS.
- Dziubinski, M., Verbrugge, R., and Dunin-Keplicz, B. (2007). Complexity issues in multiagent logics. *Fundamenta Informaticae*, 75(1-4):239–262.

- Esteve, M., Rodríguez-Aguilar, J., Rosell, B., and Arcos, J. (2004). AMELI: An agent-based middleware for electronic institutions. In *Proceedings of AAMAS 2004*, pages 236–243, New York, US.
- Fagin, R., Halpern, J. Y., Moses, Y., and Vardi, M. Y. (1995a). *Reasoning about Knowledge*. MIT Press: Cambridge, MA.
- Fagin, R., Halpern, J. Y., Moses, Y., and Vardi, M. Y. (1995b). *Reasoning about Knowledge*. MIT Press.
- Fall, K. (2003). A delay-tolerant network architecture for challenged internets. In *Proceedings of the 2003 conference on Applications, technologies, architectures, and protocols for computer communications, SIGCOMM '03*, pages 27–34, New York, NY, USA. ACM.
- Ferber, J. (1999). *Multi-agent systems: an introduction to distributed artificial intelligence*, volume 1. Addison-Wesley Reading.
- Fisher, M. (2008). Temporal representation and reasoning. In van Harmelen, F., Lifschitz, V., and Porter, B., editors, *Handbook of Knowledge Representation*, pages 513–550. Elsevier.
- Fisher, M. D., Gabbay, D. M., and Vila, L. (2005). *Handbook of temporal reasoning in artificial intelligence*, volume 1. Elsevier.
- Goranko, V., Jamroga, W., and Turrini, P. (2013). Strategic games and truly playable effectivity functions. *Autonomous Agents and Multi-Agent Systems*, 26(2):288–314.
- Goranko, V. and Shkatov, D. (2009). Tableau-based decision procedures for logics of strategic ability in multiagent systems. *ACM Trans. Comput. Log.*, 11(1).
- Goranko, V. and van Drimmelen, G. (2006). Complete axiomatization and decidability of alternating-time temporal logic. *Theoretical Computer Science*, 353(1):93–117.
- Grant, J., Kraus, S., Wooldridge, M., and Zuckerman, I. (2014). Manipulating games by sharing information. *Studia Logica*, 102(2):267–295.
- Grossi, D., Royakkers, M. M. L., and Dignum, F. (2007). Organizational structure and responsibility. *Artificial Intelligence and Law*, 15(3):223–249.
- Halpern, J. and Moses, Y. (1992). A guide to completeness and complexity for modal logics of knowledge and belief. *Artificial Intelligence*, 54:319–379.
- Halpern, J. and Vardi, M. (1989). The complexity of reasoning about knowledge and time. i. lower bounds. *Journal of Computer System Sciences*, 38(1):195–237.
- Harrenstein, P., van der Hoek, W., Meyer, J.-J., and Witteveen, C. (2001). Boolean games. In *Proceedings of the 8th conference on Theoretical aspects of rationality and knowledge*, pages 287–298. Morgan Kaufmann Publishers Inc.
- Hu, Y.-C. and Perrig, A. (2004). A survey of secure wireless ad hoc routing. *IEEE Security and Privacy*, 2(3):28–39.
- Jamroga, W. and Ågotnes, T. (2007). Constructive knowledge: What agents can achieve under incomplete information. *Journal of Applied Non-Classical Logics*, 17(4):423–475.
- Jamroga, W. and van der Hoek, W. (2004). Agents that know how to play. *Fundamenta Informaticae*, 63(2–3):185–219.
- Jennings, N. R. (1993). Commitments and conventions: The foundation of coordination in multi-agent systems. *The knowledge engineering review*, 8:223–250.
- Jones, A. J. I. and Sergot, M. (1993). On the characterization of law and computer systems. In Meyer, J.-J. C. and Wieringa, R., editors, *Deontic Logic in Computer Science: Normative System Specification*, pages 275–307. John Wiley & Sons.
- Kennedy, W. G., Bugajska, M. D., Harrison, A. M., and Trafton, J. G. (2009). “like-me” simulation as an effective and cognitively plausible basis for social robotics. *International Journal of Social Robotics*, 1(2):181–194.
- Kraus, S. (1997). Negotiation and cooperation in multi-agent environments. *Artificial Intelligence*, 94(1):79–97.

- Lilien, L., Kamal, Z., Bhuse, V., and Gupta, A. (2007). The concept of opportunistic networks and their research challenges in privacy and security. In Makki, S., Reiher, P., Makki, K., Pissinou, N., and Makki, S., editors, *Mobile and Wireless Network Security and Privacy*, pages 85–117. Springer US.
- Moses, Y. and Tennenholz, M. (1995). Artificial social systems. *Computers and AI*, 14(6):533–562.
- Nash, J. (1950). Equilibrium points in n-person games. *Proceedings of the National Academy of Sciences U.S.A.*, 36:48–49.
- Osborne, M. and Rubinstein, A. (1994). *A Course in Game Theory*. MIT Press.
- Papadimitriou, C. (1994). *Computational Complexity*. Addison Wesley : Reading.
- Pauly, M. (2001a). *Logic for Social Software*. PhD thesis, University of Amsterdam.
- Pauly, M. (2001b). A logical framework for coalitional effectivity in dynamic procedures. *Bulletin of Economic Research*, 53(4):305–324.
- Pauly, M. (2002). A modal logic for coalitional power in games. *Journal of Logic and Computation*, 12(1):149–166.
- Pelusi, L., Passarella, A., and Conti, M. (2006). Opportunistic Networking: Data Forwarding in Disconnected Mobile Ad Hoc Networks. *IEEE Communications Magazine*, 44(11):134–141.
- Peters, H. and Vrieze, O., editors (1987). *Surveys in Game Theory and Related Topics*. CWI, Amsterdam.
- Rao, A. S. (1996). Decision procedures for propositional linear-time belief-desire-intention logics. In *Intelligent Agents II: Agent Theories, Architectures, and Languages*, pages 33–48.
- Resnick, P. and Varian, H. R. (1997). Recommender systems. *Communications of the ACM*, 40(3):56–58.
- Royer, E. M. and Toh, C.-K. (1999). A review of current routing protocols for ad-hoc mobile wireless networks. *IEEE Personal Communications*, 6:46–55.
- Schewe, S. (2008). ATL* satisfiability is 2ExpTime-complete. In *Proceedings of the 35th International Colloquium on Automata, Languages and Programming, Part II (ICALP 2008), 6–13 July, Reykjavik, Iceland*, volume 5126 of *Lecture Notes in Computer Science*, pages 373–385. Springer-Verlag.
- Schobbens, P. Y. (2004). Alternating-time logic with imperfect recall. *Electronic Notes in Theoretical Computer Science*, 85(2):82–93.
- Shoham, Y. and Leyton-Brown, K. (2009). *Multiagent Systems - Algorithmic, Game-Theoretic, and Logical Foundations*. Cambridge University Press.
- Shoham, Y. and Tennenholtz, M. (1992). On the synthesis of useful social laws for artificial agent societies. In *Proceedings of the Tenth National Conference on Artificial Intelligence (AAAI-92)*, San Diego, CA.
- Shoham, Y. and Tennenholtz, M. (1995). On social laws for artificial agent societies: off-line design. *Artif. Intell.*, 73(1-2):231–252.
- Smiley, M. (2011). Collective responsibility. In Zalta, E. N., editor, *The Stanford Encyclopedia of Philosophy*. <http://plato.stanford.edu/archives/fall2011/entries/collective-responsibility/>, fall 2011 edition.
- Tambe, M. (1997). Agent architectures for flexible, practical teamwork. In *Proceedings of the National Conference on Artificial Intelligence*, pages 22–28.
- Trist, E. (1981). The evolution of socio-technical systems. *Occasional paper*, 2:1981.
- van Benthem, J., Ghosh, S., and Verbrugge, R., editors (2015). *Models of Strategic Reasoning*. Number 8972 in LNCS. Springer.
- van der Hoek, W., Roberts, M., and Wooldridge, M. (2007). Social laws in alternating time: Effectiveness, feasibility and synthesis. *Synthese*, 156(1):1–19.

- van der Hoek, W. and Wooldridge, M. (2002). Tractable multiagent planning for epistemic goals. In Castelfranchi, C. and Johnson, W., editors, *Proceedings of the First International Joint Conference on Autonomous Agents and Multi-Agent Systems (AAMAS-02)*, pages 1167–1174. ACM Press, New York.
- van der Hoek, W. and Wooldridge, M. (2003). Cooperation, knowledge and time: Alternating-time Temporal Epistemic Logic and its applications. *Studia Logica*, 75(1):125–157.
- van Otterloo, S. and Jonker, G. (2004). On Epistemic Temporal Strategic Logic. *Electronic Notes in Theoretical Computer Science*, XX:35–45. Proceedings of LCMAS’04.
- Walther, D., Lutz, C., Wolter, F., and Wooldridge, M. (2006). ATL satisfiability is indeed EXPTIME-complete. *Journal of Logic and Computation*, 16(6):765–787.
- Wooldridge, M. (2009). *An introduction to multiagent systems*. John Wiley & Sons.
- Wooldridge, M. (2013). Intelligent agents. In Weiss, G., editor, *Multiagent Systems (second edition)*, chapter 1. MIT Press.
- Wooldridge, M., Endriss, U., Kraus, S., and Lang, J. (2013). Incentive engineering for boolean games. *Artificial Intelligence*, 195(0):418 – 439.
- Wooldridge, M. and Jennings, N. R. (1995). Intelligent agents: Theory and practice. *The knowledge engineering review*, 10(02):115–152.
- Wooldridge, M. and van der Hoek, W. (2005). On obligations and normative ability: Towards a logical analysis of the social contract. *J. Applied Logic*, 3(3-4):396–420.

List of Publications Contributing to the Thesis

1. Bulling, N. and Hindriks, K. V. (2011). Taming the complexity of linear time BDI logics. In *Proceedings of the 10th International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS 2011)*, pages 275–282, Taipei, Taiwan. ACM Press
2. Bulling, N. and Dastani, M. (2011). Verification and implementation of normative behaviours in multi-agent systems. In *IJCAI 2011, Proceedings of the 22nd International Joint Conference on Artificial Intelligence, Barcelona, Catalonia, Spain, July 16-22, 2011*, pages 103–108, Barcelona, Spain. IJCAI/AAAI
3. Bulling, N. and Jamroga, W. (2011). Alternating epistemic mu-calculus. In *IJCAI 2011, Proceedings of the 22nd International Joint Conference on Artificial Intelligence, Barcelona, Catalonia, Spain, July 16-22, 2011*, pages 109–114, Barcelona, Spain. IJCAI/AAAI
4. Bulling, N., Dastani, M., and Knobbout, M. (2013a). Monitoring norm violations in multi-agent systems. In *Proc. of the 12th Int. Conf. on Autonomous Agents and Multi-Agent Systems (AAMAS 2013)*, pages 491–498, Saint Paul, Minnesota, USA. IFAAMAS, ACM Press
5. Bulling, N. and Dastani, M. (2013). Coalitional responsibility in strategic settings. In Leite, J. and Son, T. C., editors, *14th Int. Workshop on Computational Logic in Multi-Agent Systems (CLIMA XIV)*, LNCS, pages 172–189, Corunna, Spain. Springer
6. Bulling, N. and Goranko, V. (2013). How to be both rich and happy: Combining quantitative and qualitative strategic reasoning about multi-player games (extended abstract). In *Proc. of the 1st International Workshop on Strategic Reasoning*, EPTCS, pages 33–41, Rome, Italy
7. Bulling, N., Ghosh, S., and Verbrugge, R. (2013b). Reaching your goals without spilling the beans: Boolean secrecy games. In *PRIMA 2013: Principles and Practice of Multi-Agent Systems - 16th International Conference, Dunedin, New Zealand, December 1-6, 2013. Proceedings*, volume 8291 of LNCS, pages 37–53, Dunedin, New Zealand. Springer
8. Bulling, N. and Jamroga, W. (2014). Comparing variants of strategic ability: how uncertainty and memory influence general properties of games. *Journal of Autonomous Agents and Multi-Agent Systems*, 28(3):474–518
9. Bulling, N. and Popovici, M. (2014). A game-theoretic approach to compute stable topologies in mobile ad-hoc networks. *Journal of Logic and Computation*, 25(3):639–667
10. Bulling, N. (2014b). A Survey of Multi-Agent Decision Making. *KI*, 28(3):147–158

11. Bulling, N., Jamroga, W., and Popovici, M. (2014). ATL* with truly perfect recall: Expressivity and validities. In *Proceedings of the 21st European Conference on Artificial Intelligence (ECAI 2014)*, volume 263 of *Frontiers in Artificial Intelligence and Applications*, pages 177–182, Prague, Czech Republic. IOS Press
12. Bulling, N. (2014a). A Boolean game based modelling of socio-technical systems. In Mueller, J. P., Weyrich, M., and Bazzan, A. L. C., editors, *MATES 2014: Multiagent System Technologies XII*, LNAI, pages 7–25. Springer
13. Bulling, N., Goranko, V., and Jamroga, W. (2015). Logics for Reasoning About Strategic Abilities in Multi-Player Games. In van Benthem, J., Ghosh, S., and Verbrugge, R., editors, *Models of Strategic Reasoning*, number 8972 in LNCS, pages 93–136. Springer