Graded Modalities in Strategy Logic[☆]

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Abstract

Strategy Logic (SL) is a logical formalism for strategic reasoning in multi-agent systems. Its main feature is that it has variables for strategies that are associated to specific agents using a binding operator. In this paper we introduce Graded Strategy Logic (GradedSL), an extension of SL by graded quantifiers over tuples of strategy variables, i.e., "there exist at least g different tuples $(x_1, ..., x_n)$ of strategies" where g is a cardinal from the set $\mathbb{N} \cup \{\aleph_0, \aleph_1, 2^{\aleph_0}\}$. We prove that the model-checking problem of GradedSL is decidable. We then turn to the complexity of fragments of GradedSL. When the g's are restricted to finite cardinals, written Graded$_{\mathbb{N}}$SL, the complexity of model-checking is no harder than for SL, i.e., it is non-elementary in the quantifier-block rank. We illustrate our formalism by showing how to count the number of different strategy profiles that are Nash equilibria (NE). By analysing the structure of the specific formulas involved, we conclude that the important problem of checking for the existence of a unique NE can be solved in 2ExpTime, which is not harder than merely checking for the existence of such an equilibrium.

Keywords: Strategic logics; Graded modalities; Nash equilibria.

1. Introduction

Strategy Logic (SL) is a powerful formalism for reasoning about strategies in multi-agent systems [3, 4]. Strategies tell an agent what to do — they are functions that prescribe an action based on the history. The key idea in SL is to treat strategies as first-order objects. A strategy x can be quantified existentially $\langle\langle x \rangle\rangle$ (read: there exists a strategy x) and universally $[[x]]$ (read: for all strategies x). Furthermore, strategies are not intrinsically glued to specific agents: the *binding* operator (α, x) allows one to bind an agent α to the strategy x. SL strictly subsumes several other logics for strategic reasoning including the well known ATL and ATL* [5]. Being a very powerful logic, SL can directly

[☆] This is an extended version of the works [1, 2].

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Email address: murano@na.infn.it (Aniello Murano) express many solution concepts [6, 4, 7, 8, 9, 10, 11, 12] among which that a strategy profile $\overline{x}$ is a Nash equilibrium, and thus also the existence of a Nash equilibrium (NE).

The Nash equilibrium is one of the most important concepts in game theory, forming the basis of much of the recent fundamental work in multi-agent decision making. A challenging and important aspect is to establish whether a game admits a *unique* NE [13, 14, 15]. This problem is relevant to the predictive power of NE since, in case there are multiple equilibria, the outcome of the game cannot be uniquely pinned down [16, 17, 18]. Unfortunately, uniqueness has mainly been established either for special cost functions [13], or for very restrictive game topologies [19]. Moreover, there is no general theory of when games have unique equilibria that can be applied to different application areas [13].

In this paper, we address and solve the problem of expressing the uniqueness of certain solution concepts (and NE in particular) in a principled and elegant way, by introducing an extension of SL called GRADEDSL. More specifically, we extend SL by replacing the quantification $\langle\langle x\rangle\rangle$ and $[\![x]\!]$ over strategy variables with *graded quantification over tuples of strategy variables*: $\langle\langle x_1, \ldots, x_n\rangle\rangle^{\geq g}$ (read $\langle\langle x_1, \ldots, x_n\rangle\rangle^{\geq g}$ as "there exist at least g different tuples $(x_1, \ldots, x_n)$ of strategies") and its dual $[\![x_1, \ldots, x_n]\!]^{<g}$, where $g \in \mathbb{N} \cup \{\aleph_0, \aleph_1, 2^{\aleph_0}\}$. Here, two tuples are different if they are different in some component, and two strategies are different if they disagree on some history. The key is being able to express uniqueness of NE is the combination of quantifying over tuples (instead of singleton variables), and adding counting (in the form of graded modalities).

As far as the expressive power of GRADEDSL concerns, we prove that counting strategies in SL is not possible in general (see Theorem 2.1). On the other hand, every formula of SL has an equivalent formula of GRADEDSL formed by replacing every quantifier $\langle\langle x\rangle\rangle$ with $\langle\langle x\rangle\rangle^{\geq 1}$. Additionally, the possibility of quantifying over tuples of strategy variables (rather than single strategies) makes the logic quite expressive.

We address the model-checking problem for GRADEDSL and prove that it is decidable. We also address the complexity of several fragments of GRADEDSL. First we consider the case in which the g's are restricted to finite cardinals, written GRADED$_{\mathbb{N}}$SL. Then we investigate the graded extension of classic fragments of SL, such as Nested-Goal SL and one-goal SL [4], while maintaining the restriction of grades over finite cardinals. Roughly speaking, the Nested-Goal restriction encompasses formulas in a special prenex normal form with a particular nested temporal structure that restricts the application of both strategy quantifiers and agent bindings; further, the one-goal restriction is obtained by forbidding any nesting and Boolean operation over bindings (see Section 2.4 for details).

We show that the complexity of the model-checking problem for GRADED$_{\mathbb{N}}$SL is no harder than for SL, i.e., it is non-elementary in the nesting depth of quantifiers. In particular, we show that model checking GRADED$_{\mathbb{N}}$SL formulas with a nesting depth $k > 0$ of blocks of quantifiers (a block of quantifiers is a maximally-consecutive sequence of quantifiers of the same type, i.e., either all existential, or all universal) is in $(k+1)$ExpTime, and that for the special case where the formula starts with a block of quantifiers, it is in kExpTime. Since many natural formulas contain a very small number of quantifiers, the complexity of the model-checking problem is not as bad as it seems. Specifically, several solution concepts can be expressed as SL formulas with a small number of quantifiers[6, 4, 7, 8, 9]. Since the existence of a NE, and the fact that there is at most one NE, can be expressed in Graded$_{\mathbb{N}}$SL using simple formulas (assuming that the agents' goals are given as LTL formulas) we are able to conclude that the problem of checking the uniqueness of a NE can be solved in 2ExpTime. Previously, it was known that existence of NE can be checked in 2ExpTime [4]. Thus, GradedSL is the first logic that can solve the existence and uniqueness of NE (as well as many other solution concepts) in 2ExpTime.

Concerning the graded Nested-Goal fragment, namely GradedSL[ng], we show that, in case the g's are restricted to finite cardinals, it has the same model-checking complexity as Nested-Goal SL, i.e., non-elementary in the *alternation number* of the quantifiers appearing in the formula. For the one-goal fragment, namely Graded$_{\mathbb{N}}$SL[1g], the model checking problem is instead 2ExpTime-complete. All model checking complexities reported so far refer to the size of the formula.

Related work. The importance of solution concepts, verifying a unique equilibrium, and the relationship with logics for strategic reasoning is discussed above. We now give some highlights from the long and active investigation of graded modalities in the formal verification community.

Graded modalities were first studied in modal logic [20] and then exported to the field of knowledge representation to allow quantitative bounds on the set of individuals satisfying a given property. Specifically, they were considered as *counting quantifiers* in first-order logics [21] and *number restrictions* in *description logics* [22]. *Graded μ-calculus*, in which immediate-successor accessible worlds are counted, was introduced to reason about graded modal logic with fixed-point operators [23]. Recently, the notion of graded modalities was extended to count the number of paths in the branching-time temporal logic formulas CTL and CTL* [24, 25].

Graded strategy quantifiers were studied in [26, 27]. However, in contrast to our work, both of these works have an intricate way of counting. The work in [26] introduced a graded extension of SL, called GSL. This logic gives a semantic definition for when two strategies should be considered equal, and counts the number of equivalence classes. While this intricate approach is justifiable, it leads to a complicated model-checking problem. Indeed, only a very weak fragment of GSL has been solved in [26], namely the vanilla restriction of the graded version of the one-goal fragment of SL [28]. There is a common belief that the one-goal fragment is not powerful enough to express the existence of a Nash Equilibrium in concurrent games. The smallest fragment that is known to be able to represent this is the so called Boolean-goal Strategy Logic, whose graded extension (in the GSL sense) has no known solution.[1]

We note that the work in [27] introduced a graded extension of ATL with two semantics for graded strategy quantifiers. Both of these semantics also employ an intricate equivalence relation on paths and sets of paths.

Finally, we mention that in the verification of reactive systems there is an orthogonal approach called module checking. [2] Module-checking for graded μ-calculus was studied in [33, 34].

Outline. The sequel of the paper is structured as follows. In Section 2 we introduce GradedSL and provide some preliminary related concepts. In Section 3 we address the model-checking problem for GradedSL and its fragments. In Section 4 we illustrate our logic by expressing the uniqueness of various solution concepts. We conclude with Section 5 in which we have a discussion and suggestions for future work.

2. Graded Strategy Logic

In this section we introduce Graded Strategy Logic, which we call GradedSL for short.

In the following we use a finite set Vr of *variables*, a finite set Ag of *agents*, and a finite set AP of *atomic propositions (atoms)*. We denote variables by x_i, x_j, etc., agents by α_i, α_j, etc., and atomic propositions by p, q, etc. The assumption that these sets are finite is simply a technical convenience: the model-checking problem (Definition 3.1) takes as input formulas and arenas with any number of variables, agents, and atoms.

2.1. Syntax

GradedSL extends SL by replacing the singleton strategy quantifiers $\langle\langle x\rangle\rangle$ and $[[x]]$ with the graded (tupled) quantifiers $\langle\langle x_1,\ldots,x_n\rangle\rangle^{\geq g}$ and $[[x_1,\ldots,x_n]]^{<g}$, respectively, where $g \in \mathbb{N} \cup \{\aleph_0, \aleph_1, 2^{\aleph_0}\}$ is called the *grade* of the quantifier. Intuitively, these are read as "there exist at least g tuples of strategies $(x_1,\ldots,x_n)$" and "all but less than g many tuples of strategies", respectively. The syntax (α, x) denotes a *binding* of the agent α to the strategy x.

Definition 2.1. GradedSL formulas *are built inductively by means of the following grammar, where* $p \in \mathrm{AP}$*,* $\alpha \in \mathrm{Ag}$*,* $x, x_1, \ldots, x_n \in \mathrm{Vr}$ *such that* $x_i \neq x_j$ *for* $i \neq j$ *and* $n \in \mathbb{N}$*, and* $g \in \mathbb{N} \cup \{\aleph_0, \aleph_1, 2^{\aleph_0}\}$*:*

$$\varphi := p \mid \neg\varphi \mid \varphi \vee \varphi \mid \mathsf{X}\,\varphi \mid \varphi\,\mathsf{U}\,\varphi \mid \langle\langle x_1,\ldots,x_n\rangle\rangle^{\geq g}\varphi \mid (\alpha, x)\varphi.$$

[1] In [29] it has been shown that, in the restricted case of turn-based structures it is possible to express the existence of Nash equilibria in m^{-}ATL* [30], a memory-full variant of ATL* (hence included in one-goal SL), but exponentially more succinct — and thus with a much more expensive model-checking algorithm. As the authors in [29] also state, it is not clear how to extend this result to the concurrent setting, even in the case of two agents.

[2] Module checking is a decision problem proposed in late 1990s to formalize verification of open systems [31]. Recently it has been showed that module checking offers a distinctly different perspective from the problem of model checking [32].

Note that GradedSL formulas are defined *w.r.t.* fixed finite sets of atomic propositions AP, agents Ag, and variables Vr.

Notation. Whenever we write $\langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq g}$ we mean that $x_i \neq x_j$ for $i \neq j$, i.e., the variables in a tuple are distinct (note that this does not mean that the strategies the variables represent are distinct).

Shorthands are derived as usual. Specifically, $\mathsf{true} \triangleq p \vee \neg p$, $\mathsf{false} \triangleq \neg\mathsf{true}$, $\mathsf{F}\,\varphi \triangleq \mathsf{true}\,\mathsf{U}\,\varphi$, and $\mathsf{G}\,\varphi \triangleq \neg\,\mathsf{F}\,\neg\varphi$. Also, we have that $[\![x_1, \ldots, x_n]\!]^{<g}\varphi \triangleq \neg\langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq g}\neg\varphi$. The operators $\langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq g}$ (resp. $[\![x_1, \ldots, x_n]\!]^{<g}$) are called *existential (resp. universal) strategy quantifiers.*

In order to define the semantics, we first define the concept of *free placeholders* in a formula, which refer to agents and variables. Intuitively, an agent or variable is free in φ if it does not have a strategy associated with it (either by quantification or binding) but one is required in order to ascertain if φ is true or not. The definition mimics that for SL [4]. It is important for defining the model-checking procedure, in particular for the encoding of strategies as trees (Definition 3.3).

Definition 2.2. *The set of* free agents *and* free variables $free(\varphi) \in 2^{\mathrm{Ag} \cup \mathrm{Vr}}$ *of a* GradedSL *formula φ is inductively defined as follows:*

- $\mathsf{free}(p) \triangleq \emptyset$*, where* $p \in \mathrm{AP}$*;*
- $\mathsf{free}(\neg\varphi) \triangleq \mathsf{free}(\varphi)$*;*
- $\mathsf{free}(\varphi_1 \vee \varphi_2) \triangleq \mathsf{free}(\varphi_1) \cup \mathsf{free}(\varphi_2)$*;*
- $\mathsf{free}(\mathsf{X}\,\varphi) \triangleq \mathrm{Ag} \cup \mathsf{free}(\varphi)$*;*
- $\mathsf{free}(\varphi_1\,\mathsf{U}\,\varphi_2) \triangleq \mathrm{Ag} \cup \mathsf{free}(\varphi_1) \cup \mathsf{free}(\varphi_2)$*;*
- $\mathsf{free}(\langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq g}\varphi) \triangleq \mathsf{free}(\varphi) \setminus \{x_1, \ldots, x_n\}$*;*
- $\mathsf{free}((\alpha, x)\varphi) \triangleq \begin{cases} \mathsf{free}(\varphi), & \textit{if } \alpha \notin \mathsf{free}(\varphi); \\ (\mathsf{free}(\varphi) \setminus \{\alpha\}) \cup \{x\}, & \textit{otherwise.} \end{cases}$

A formula φ without free agents (resp., variables), i.e., with $\mathsf{free}(\varphi) \cap \mathrm{Ag} = \emptyset$ *(resp.,* $\mathsf{free}(\varphi) \cap \mathrm{Vr} = \emptyset$*), is called* agent-closed *(resp.,* variable-closed*). If φ is both agent- and variable-closed, it is called a* sentence*.*

Roughly, the *quantifier rank* of φ is the maximum, over all paths in the parse-tree of φ, of the number of strategy quantifiers that appear on the path, e.g., $\langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq g}(\alpha_1, x_1) \ldots (\alpha_n, x_n) \bigwedge_{i=1}^{n}(\langle\!\langle \mathsf{y} \rangle\!\rangle(\alpha_i, \mathsf{y})\psi_i) \to \psi_i$ has quantifier rank 2 if each ψ_i is quantifier free.

Definition 2.3. *The* quantifier rank $\mathsf{qr}(\varphi) \in \mathbb{N}$ *of a* GradedSL *formula φ is inductively defined as follows:*

- $\mathsf{qr}(p) \triangleq 0$*, where* $p \in \mathrm{AP}$*;*

- $\mathsf{qr}(\mathsf{OP}\varphi) \triangleq \mathsf{qr}(\varphi)$, *where* $\mathsf{OP} \in \{\neg, \mathsf{X}, \flat\}$*;*
- $\mathsf{qr}(\varphi_1 \mathsf{OP} \varphi_2) \triangleq \mathsf{max}(\mathsf{qr}(\varphi_1), \mathsf{qr}(\varphi_2))$ *where* $\mathsf{OP} \in \{\vee, \mathsf{U}\}$*;*
- $\mathsf{qr}(\langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq g} \varphi) \triangleq \mathsf{qr}(\varphi) + 1$.

Roughly, a *quantifier-block of* φ is a maximally-consecutive sequence of quantifiers in φ of the same type (*i.e.*, either all existential, or all universal). The *quantifier-block rank* of a formula is like the quantifier rank except that a quantifier block of j quantifiers contributes 1 instead of j to the count. The formal definition follows:

Definition 2.4. *The* quantifier-block rank $\mathsf{qbr}(\varphi) \in \mathbb{N}$ *of a* GradedSL *formula* φ *that uses the shorthand for universal strategy quantifiers is inductively defined as follows:*

- $\mathsf{qbr}(p) \triangleq 0$, *where* $p \in \mathrm{AP}$*;*
- $\mathsf{qbr}(\mathsf{OP}\varphi) \triangleq \mathsf{qbr}(\varphi)$, *where* $\mathsf{OP} \in \{\neg, \mathsf{X}, \flat\}$*;*
- $\mathsf{qbr}(\varphi_1 \mathsf{OP} \varphi_2) \triangleq \mathsf{max}(\mathsf{qbr}(\varphi_1), \mathsf{qbr}(\varphi_2))$ *where* $\mathsf{OP} \in \{\vee, \mathsf{U}\}$*;*
- $\mathsf{qbr}(\langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq g} \varphi) \triangleq \mathsf{qbr}(\varphi)$ *if* φ *begins with an existential strategy quantifier, and* $\mathsf{qbr}(\varphi) + 1$ *otherwise.*
- $\mathsf{qbr}([\![x_1, \ldots, x_n]\!]^{<g} \varphi) \triangleq \mathsf{qbr}(\varphi)$ *if* φ *begins with a universal strategy quantifier, and* $\mathsf{qbr}(\varphi) + 1$ *otherwise.*

Note that we treat $\neg\langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq g} \neg\varphi$ differently to $[\![x_1, \ldots, x_n]\!]^{<g} \varphi$. Thus, one should choose the existential and universal quantifiers judiciously in order to obtain a low quantifier-block rank.

2.2. Models

Sentences of GradedSL are interpreted over *arenas* [3], just as for ATL and SL [5, 4].

Definition 2.5. *An* arena *over fixed sets of atomic proposition* AP *and agents* Ag *is a tuple* $\mathcal{A} \triangleq \langle \mathrm{Ac}, \mathrm{St}, s_I, \mathsf{ap}, \mathsf{tr} \rangle$*, where:*

- Ac *is a finite set of* actions*;*
- St *is a finite set of* states*;*
- $s_I \in \mathrm{St}$ *is the* initial state*;*
- $\mathsf{ap} : \mathrm{St} \to 2^{\mathrm{AP}}$ *is the* labeling function *mapping each state to the set of atomic propositions true in that state;*

[3] This is sometimes called a Concurrent Game Structure.

- *Let* $\mathrm{Dc} \triangleq \mathrm{Ag} \to \mathrm{Ac}$ *be the set of* decisions, i.e., *functions describing the choice of an action by every agent. Then,* $\mathsf{tr} : \mathrm{Dc} \to (\mathrm{St} \to \mathrm{St})$ *is a* transition function *mapping every decision* $\delta \in \mathrm{Dc}$ *to a function* $\mathsf{tr}(\delta) : \mathrm{St} \to \mathrm{St}$.

We will usually take the set Ag of agents to be $\{\alpha_1, \ldots, \alpha_n\}$. A *path (from s)* is a finite or infinite non-empty sequence of states $s_1 s_2 \ldots$ such that $s = s_1$ and for every i there exists a decision δ with $\mathsf{tr}(\delta)(s_i) = s_{i+1}$. Given a path $\pi = s_1 s_2 \ldots$, with $\lambda(\pi)$ we denote the *label of* π as a sequence of sets of atomic propositions $\pi_1, \pi_2, \ldots$ where $\mathsf{ap}(s_1) = \pi_1$, $\mathsf{ap}(s_2) = \pi_2$, and so on. The set of paths starting with s is denoted $\mathrm{Pth}(s)$. The set of finite paths from s, called the *histories (from s)*, is denoted $\mathrm{Hst}(s)$. A *strategy (from s)* is a function $\sigma \in \mathrm{Str}(s) \triangleq \mathrm{Hst}(s) \to \mathrm{Ac}$ that prescribes which action has to be performed given a history. We write $\mathrm{Pth}, \mathrm{Hst}, \mathrm{Str}$ for the set of all paths, histories, and strategies (no matter where they start). We use the standard notion of equality between strategies [35], i.e., $\sigma_1 = \sigma_2$ iff for all $\rho \in \mathrm{Hst}$, $\sigma_1(\rho) = \sigma_2(\rho)$. This extends to equality between two n-tuples of strategies in the natural way, i.e., coordinate-wise. There is a subtlety in this definition, i.e., two strategies are different if they differ on some history ρ, even if that history is not reachable using either of the strategies.

2.3. Semantics

As for SL, the interpretation of a GradedSL formula requires a valuation of its free placeholders.

Definition 2.6. *An* assignment (from s) *is a function* $\chi \in \mathrm{Asg}(s) \triangleq (\mathrm{Vr} \cup \mathrm{Ag}) \to \mathrm{Str}(s)$ *mapping variables and agents to strategies.*

We denote by $\chi[e \mapsto \sigma]$, with $e \in \mathrm{Vr} \cup \mathrm{Ag}$ and $\sigma \in \mathrm{Str}(s)$, the assignment that differs from χ only in the fact that e maps to σ. Extend this definition to tuples: for $\overline{e} = (e_1, \ldots, e_n)$ with $e_i \neq e_j$ for $i \neq j$, define $\chi[\overline{e} \mapsto \overline{\sigma}]$ to be the assignment that differs from χ only in the fact that e_i maps to σ_i (for each i).

Since an assignment ensures that all free variables are associated with strategies, it induces a play.

Definition 2.7. *Let* $\chi \in \mathrm{Asg}(s)$ *be an assignment. By* (χ, s)-play *we denote the path* $\pi \in \mathrm{Pth}(s)$ *such that, for all* $i \in \mathbb{N}$, *it holds that* $\pi_{i+1} = \mathsf{tr}(\mathsf{dc})(\pi_i)$, *where* $\mathsf{dc}(\alpha) \triangleq \chi(\alpha)(\pi_{\leq i})$, *for* $\alpha \in \mathrm{Ag}$. *The function* $\mathsf{play} : \mathrm{Asg} \times \mathrm{St} \to \mathrm{Pth}$, *with* $\mathsf{dom}(\mathsf{play}) \triangleq \{(\chi, s) : \chi \in \mathrm{Asg}(s)\}$, *maps* (χ, s) *to the* (χ, s)*-play* $\mathsf{play}(\chi, s) \in \mathrm{Pth}(s)$.

The notation $\pi_{\leq i}$ (resp. $\pi_{<i}$) denotes the prefix of the sequence π of length i (resp. $i - 1$). Similarly, the notation π_i denotes the ith symbol of π. Thus, $\mathsf{play}(\chi, s)_i$ is the ith state on the play determined by χ from s.

The following definition of χ_i says how to interpret an assignment χ starting from a point i along the play, i.e., for each placeholder e, take the action the strategy $\chi(e)$ would do if it were given the prefix of the play up to i followed by the current history.

Definition 2.8. *For $\chi \in \mathrm{Asg}(s)$ and $i \in \mathbb{N}$, writing $\rho \triangleq \mathsf{play}(\chi, s)_{\leq i}$ (the prefix of the play up to i) and $t \triangleq \mathsf{play}(\chi, s)_i$ (the last state of ρ) define $\chi_i \in \mathrm{Asg}(t)$ to be the assignment from t that maps $e \in \mathrm{Vr} \cup \mathrm{Ag}$ to the strategy that maps $h \in \mathrm{Hst}(t)$ to the action $\chi(e)(\rho_{<i} \cdot h)$.*

The semantics of GradedSL mimics the one for SL as given in [4]. Given an arena $\mathcal{A}$, for all states $s \in \mathrm{St}$ and assignments $\chi \in \mathrm{Asg}(s)$, we now define the relation $\mathcal{A}, \chi, s \models \varphi$, read φ *holds at* s *in* $\mathcal{A}$ *under* χ.

Definition 2.9. *Fix an arena $\mathcal{A}$. For all states $s \in \mathrm{St}$ and assignments $\chi \in \mathrm{Asg}(s)$, the relation $\mathcal{A}, \chi, s \models \varphi$ is defined inductively on the structure of φ:*

- $\mathcal{A}, \chi, s \models p$ *iff* $p \in \mathsf{ap}(s)$;
- $\mathcal{A}, \chi, s \models \neg\varphi$ *iff* $\mathcal{A}, \chi, s \not\models \varphi$;
- $\mathcal{A}, \chi, s \models \varphi_1 \vee \varphi_2$ *iff* $\mathcal{A}, \chi, s \models \varphi_1$ *or* $\mathcal{A}, \chi, s \models \varphi_2$;
- $\mathcal{A}, \chi, s \models \mathsf{X}\,\varphi$ *iff* $\mathcal{A}, \chi_1, \mathsf{play}(\chi, s)_1 \models \varphi$;
- $\mathcal{A}, \chi, s \models \varphi_1 \,\mathsf{U}\, \varphi_2$ *iff there is* $i \in \mathbb{N}$ *such that* $\mathcal{A}, \chi_i, \mathsf{play}(\chi, s)_i \models \varphi_2$ *and, for all* $j \in \mathbb{N}$ *with* $j < i$, *it holds that* $\mathcal{A}, \chi_j, \mathsf{play}(\chi, s)_j \models \varphi_1$;
- $\mathcal{A}, \chi, s \models (\alpha, x)\varphi$ *iff* $\mathcal{A}, \chi[\alpha \mapsto \chi(x)], s \models \varphi$;
- $\mathcal{A}, \chi, s \models \langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g}\varphi$ *iff there exist g many n-tuples of strategies $\overline{\sigma_i}$ ($0 \leq i < g$) such that:*
  - $\overline{\sigma_i} \neq \overline{\sigma_j}$ *for* $i \neq j$;
  - $\mathcal{A}, \chi[\overline{x} \mapsto \overline{\sigma_i}], s \models \varphi$ *for* $0 \leq i < g$ *and* $\overline{x} = (x_1, \ldots, x_n)$.

Intuitively, $\langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g}\varphi$ expresses that the number of distinct tuples of strategies that satisfy φ is at least g.

As usual, if χ and χ' agree on $\mathsf{free}(\varphi)$, then $\mathcal{A}, \chi, s \models \varphi$ if and only if $\mathcal{A}, \chi', s \models \varphi$, i.e., the truth of φ does not depend on the values the assignment takes on placeholders that are not free. Thus, for a sentence φ we write $\mathcal{A}, s \models \varphi$ to mean that $\mathcal{A}, \chi, s \models \varphi$ for some (equivalently, for all) assignments χ. Also, we write $\mathcal{A} \models \varphi$ to mean $\mathcal{A}, s_I \models \varphi$ where s_I is the initial state of $\mathcal{A}$.

2.4. Fragments of GradedSL

In this section we introduce various syntactic fragments of GradedSL. Obviously SL can be considered a fragment of GradedSL: note that the GradedSL quantifier $\langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g}$ in case $g = 1$ and $n = 1$ has the same semantics as the SL quantifier $\langle\langle x_1 \rangle\rangle$. The next result shows that GradedSL is strictly more expressive than SL, i.e., there is a GradedSL sentence whose models are not the set of models of any SL sentence.

Theorem 2.1. GradedSL *is strictly more expressive than* SL.

Proof. Fix $\mathrm{Ag} = \{\alpha\}$, $\mathrm{AP} = \{p\}$, $\mathrm{St} = \{s\}$, $s_I = s$, $\mathsf{ap}(s) = \{p\}$. Define $\mathcal{A} = \langle \mathrm{Ac}_A, \mathrm{St}, s_I, \mathsf{ap}, \mathsf{tr}_A \rangle$, where $\mathrm{Ac}_A = \{0\}$, and $\mathsf{tr}_A(\delta)(s) = s$ for every decision δ; and $\mathcal{B} = \langle \mathrm{Ac}_B, \mathrm{St}, s_I, \mathsf{ap}, \mathsf{tr}_B \rangle$, where $\mathrm{Ac}_B = \{0, 1\}$, and $\mathsf{tr}_B(\delta)(s) = s$ for every decision δ. Thus, each arena consists of a single state with self-loops, the difference being that in $\mathcal{B}$ there are two actions while in $\mathcal{A}$ there is only a single action.

Consider the GradedSL formula $\neg\langle\langle x \rangle\rangle^{\geq 2}\mathsf{true}$. Note that $\mathcal{A} \models \neg\langle\langle x \rangle\rangle^{\geq 2}\mathsf{true}$ (since there is only a single strategy in $\mathcal{A}$), while $\mathcal{B} \not\models \neg\langle\langle x \rangle\rangle^{\geq 2}\mathsf{true}$ (since there are at least two, and in fact $2^{\aleph_0}$ many, strategies in $\mathcal{B}$).

Let χ_A be the unique assignment in $\mathcal{A}$, i.e., that maps α and every variable in Vr to the strategy σ defined by $\sigma(h) = 0$ for all histories h. We claim that, for every SL formula φ, if $\mathcal{A}, \chi_A, s \models \varphi$ then, for all assignments χ we have that $\mathcal{B}, \chi, s \models \varphi$. Thus, in particular, no SL sentence can distinguish between $\mathcal{A}$ and $\mathcal{B}$, and the theorem follows.

One can easily prove the claim by induction on the structure of an SL formula. Alternatively, one may note that $\mathcal{A}$ and $\mathcal{B}$ are locally-isomorphic, and thus agree on all SL formulas (see [36, Section 3] for the definition and properties of "local-isomorphism").[4] □

Recall that SL has a few natural syntactic fragments, the most powerful of which is SL[NG] (here "NG" stands for Nested-Goal). Recall that in SL[NG], we require that bindings and quantifications appear in exhaustive blocks. I.e., whenever there is a quantification over a variable in a formula ψ it is part of a consecutive sequence of quantifiers that covers all of the free variables that appear in ψ, and whenever an agent is bound to a strategy then it is part of a consecutive sequence of bindings of all agents to strategies. Also, formulas with free agents are not allowed. We define GradedSL[NG] in a similar way, as follows.

A *quantification prefix* over a set $\mathrm{V} \subseteq \mathrm{Vr}$ of variables is a sequence $\wp$ from the set

$$\{\langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g}, [[x_1, \ldots, x_n]]^{<g} : n \in \mathbb{N}, x_1, \ldots, x_n \in \mathrm{V} \wedge g \in \mathbb{N} \cup \{\aleph_0, \aleph_1, 2^{\aleph_0}\}\}^*$$

such that each $x \in \mathrm{V}$ occurs exactly once in $\wp$. A *binding prefix* is a sequence $\flat \in \{(\alpha, x) : \alpha \in \mathrm{Ag} \wedge x \in \mathrm{Vr}\}^*$ such that each $\alpha \in \mathrm{Ag}$ occurs exactly once in $\flat$. We denote the set of binding prefixes by Bn, and the set of quantification prefixes over V by Qn(V).

Definition 2.10. GradedSL[NG] *formulas are built inductively using the following grammar, with $p \in \mathrm{AP}$, $\wp \in \mathrm{Qn}(\mathrm{V})$ ($\mathrm{V} \subseteq \mathrm{Vr}$), and $\flat \in \mathrm{Bn}$:*

$$\varphi ::= p \mid \neg\varphi \mid \varphi \vee \varphi \mid \mathsf{X}\,\varphi \mid \varphi\,\mathsf{U}\,\varphi \mid \wp\varphi \mid \flat\varphi,$$

where in the rule $\wp\varphi$ we require that φ is agent-closed and $\wp \in \mathsf{Qn}(\mathsf{free}(\varphi))$. In this case we call $\wp\varphi$ a principal *formula.*

[4] We thank an anonymous reviewer for pointing this out.

Formulas of GRADEDSL[NG] can be classified according to their *alternation number*, i.e., the maximum number of quantifier switches in a quantification prefix. [5] Formally:

Definition 2.11. *The* alternation number $\mathsf{alt}(\varphi)$ *of a* GRADEDSL[NG] *formula* φ *is defined as follows:*

- $\mathsf{alt}(p) \triangleq 0$*, where* $p \in \mathrm{AP}$*;*
- $\mathsf{alt}(\mathsf{OP}\varphi) \triangleq \mathsf{alt}(\varphi)$*, where* $\mathsf{OP} \in \{\neg, \mathsf{X}, \flat\}$*;*
- $\mathsf{alt}(\varphi_1 \mathsf{OP} \varphi_2) \triangleq \mathsf{max}(\mathsf{alt}(\varphi_1), \mathsf{alt}(\varphi_2))$ *where* $\mathsf{OP} \in \{\vee, \mathsf{U}\}$*;*
- $\mathsf{alt}(\wp\varphi) \triangleq \mathsf{max}(\mathsf{alt}(\varphi), \mathsf{alt}(\wp))$ *where* $\wp = \wp_1 \ldots \wp_{|\wp|-1}$ *is a quantification prefix and* $\mathsf{alt}(\wp) \triangleq \sum_{i=1}^{|\wp|-1} \mathsf{switch}(\wp_i, \wp_{i+1})$*, where* $\mathsf{switch}(Q, Q') = 0$ *if* Q *and* Q' *are either both universal or both existential quantifiers, and* 1 *otherwise* [6]*.*

Another important fragment of SL is SL[1G] (here "1G" stands for One-Goal). Intuitively, SL[1G] is the fragment of GRADEDSL[NG] in which quantification is immediately followed by binding. The importance of this fragment stems from the fact that it strictly includes ATL* while maintaining the same complexity for both the model checking and the satisfiability problems, *i.e.* 2EXPTIME-COMPLETE [28, 4]. However, it is commonly believed that Nash Equilibrium cannot be expressed in this fragment. Similarly, we give the following definition of GRADEDSL[1G]:

Definition 2.12. GRADEDSL[1G] *formulas are built inductively using the following grammar, with* $p \in \mathrm{AP}$*,* $\wp \in \mathrm{Qn}(\mathrm{V})$ *(*$\mathrm{V} \subseteq \mathrm{Vr}$*), and* $\flat \in \mathrm{Bn}$*:*

$$\varphi ::= p \mid \neg\varphi \mid \varphi \vee \varphi \mid \mathsf{X}\,\varphi \mid \varphi\,\mathsf{U}\,\varphi \mid \wp\flat\varphi,$$

where $\wp$ *is a quantification prefix over* $\mathsf{free}(\flat\varphi)$*.*

Recall (see [4]) that ATL* can be viewed as the fragment of SL[1G] in which occurrences of $\wp\flat$ are of the form

$$\langle\langle x_1 \rangle\rangle \cdots \langle\langle x_m \rangle\rangle [[x_{m+1}]] \cdots [[x_n]] (\beta_1, x_1)(\beta_2, x_2) \cdots (\beta_n, x_n),$$

where $\{\beta_1, \cdots, \beta_n\} = \mathrm{Ag}$ for $n = |\mathrm{Ag}|$, and $x_i \neq x_j$ for all $i \neq j$. In the usual notation of ATL*, the operator $\wp\flat$ is written $\langle\langle A \rangle\rangle$ where $A = \{\beta_1, \cdots, \beta_m\}$. In a similar way, but using tuples of strategies, we define a graded extension of ATL* as a fragment of GRADED$_{\mathbb{N}}$SL[1G]:

[5] In [4] the alternation number is described for all formulas of SL. Here, we only define it for GRADEDSL[NG] since this is enough for our purposes.

[6] Observe that formulas of the form $\wp\varphi$ have no free variables and thus one cannot form formulas of the form $\wp'\wp\varphi$.

Definition 2.13. GradedATL* *formulas are built inductively using the following grammar, with* $p \in \mathrm{AP}$*,* $\wp$ *is of the form* $\langle\!\langle x_1, \cdots, x_m \rangle\!\rangle^{\geq g}[\![x_{m+1}, \cdots, x_n]\!]$ *where* $n = |\mathrm{Ag}|$*,* $m \leq n$*,* $g \in \mathbb{N} \cup \{\aleph_0, \aleph_1, 2^{\aleph_0}\}$ *and* $x_i \neq x_j$ *for all* $i \neq j$*, and* $\flat$ *is of the form* $(\beta_1, x_1)(\beta_2, x_2) \cdots (\beta_n, x_n)$ *where* $\{\beta_1, \cdots, \beta_n\} = \mathrm{Ag}$*:*

$$\varphi ::= p \mid \neg\varphi \mid \varphi \vee \varphi \mid \mathsf{X}\, \varphi \mid \varphi\, \mathsf{U}\, \varphi \mid \wp\flat\varphi.$$

Finally, an important fragment of GradedSL (in which one can express uniqueness of strategy profiles) is when all grades are in $\mathbb{N}$.

Definition 2.14. *Let* Graded$_\mathbb{N}$SL*,* Graded$_\mathbb{N}$SL[ng] Graded$_\mathbb{N}$SL[1g]*, and* Graded$_\mathbb{N}$ATL* *denote the corresponding fragments in which all grades are from the set* $\mathbb{N}$*.*

3. Model-checking GradedSL

In this section we study the model-checking problem for GradedSL and show that it is decidable with a time-complexity that is non-elementary (i.e., not bounded by any fixed tower of exponentials). However, it is elementary if the number of blocks of quantifiers is fixed.

Definition 3.1. *The* model-checking problem for GradedSL (respectively, GradedSL[ng]) *is the following decision problem: given a formula* φ *from* GradedSL *(respectively,* GradedSL[ng]*) over some finite sets of atoms* AP*, agents* Ag*, and variables* Vr*, and given an arena* $\mathcal{A}$ *over the sets* AP *and* Ag*, decide whether* $\mathcal{A} \models \varphi$*.*

When measuring computational complexity, the grades in formulas are written in unary.

For the algorithmic procedures, we follow an *automata-theoretic approach* [37], reducing the decision problem for the logic to the emptiness problem of an automaton. The procedure we propose here extends that used for SL in [4]. The only case that is different is the new graded quantifier over tuples of strategies, i.e., we show how to convert a GradedSL formula φ into an automaton that accepts exactly the (tree encodings) of the assignments that satisfy φ.

Tree Automata. A Σ-*labeled* Υ-*tree* T is a pair $\langle T, V \rangle$ where $T \subseteq \Upsilon^+$ is prefix-closed (i.e., if $t \in T$ and $s \in \Upsilon^+$ is a prefix of t then also $s \in T$), and $V : T \to \Sigma$ is a labeling function. Note that every word $w \in \Upsilon^+ \cup \Upsilon^\omega$ with the property that every prefix of w is in T, can be thought of as a path in T. Infinite paths are called *branches*. *Nondeterministic tree automata* (Nta) are a generalization to infinite trees of the classical automata on words [38]. *Alternating tree automata* (Ata) are a further generalization of nondeterministic tree automata [39]. Intuitively, on visiting a node of the input tree, while an Nta sends exactly one copy of itself to each of the successors of the node, an Ata can send several copies to the same successor. We use the parity acceptance condition [37].

For a set X, let $\mathtt{B}^+(X)$ be the set of positive Boolean formulas over X, including the constants **true** and **false**. A set $Y \subseteq X$ satisfies a formula $\theta \in \mathtt{B}^+(X)$, written $Y \models \theta$, if assigning **true** to elements in Y and **false** to elements in $X \setminus Y$ makes θ true.

Definition 3.2. *An Alternating Parity Tree-Automaton (*Apt*) is a tuple* $\mathcal{M} \triangleq \langle \Sigma, \Delta, \mathrm{Q}, \delta, q_o, \mathrm{F} \rangle$*, where*

- Σ *is the* input alphabet*,*
- Δ *is a set of* directions*,*
- Q *is a finite set of* states*,*
- $q_o \in \mathrm{Q}$ *is an* initial state*,*
- $\delta : \mathrm{Q} \times \Sigma \to \mathtt{B}^+(\Delta \times \mathrm{Q})$ *is an* alternating transition function*, and*
- F*, an* acceptance condition*, is of the form* $(\mathrm{F}_1, \ldots, \mathrm{F}_k) \in (2^{\mathrm{Q}})^+$ *where* $\mathrm{F}_1 \subseteq \mathrm{F}_2 \ldots \subseteq \mathrm{F}_k = \mathrm{Q}$.

The set $\Delta \times \mathrm{Q}$ is called the set of *moves*. An Nta is an Ata in which each conjunction in the transition function δ has exactly one move (d, q) associated with each direction d.

An *input tree* for an Apt is a Σ-labeled Δ-tree $\mathsf{T} = \langle \mathrm{T}, \mathsf{v} \rangle$. A *run* of an Apt on an input tree $\mathsf{T} = \langle \mathrm{T}, \mathsf{v} \rangle$ is a $(\Delta \times \mathrm{Q})$-tree R such that, for all nodes $x \in \mathrm{R}$, where $x = (d_1, q_1) \ldots (d_n, q_n)$ (for some $n \in \mathbb{N}$), it holds that *(i)* $y \triangleq (d_1, \ldots, d_n) \in \mathrm{T}$ and *(ii)* there is a set of moves $\mathrm{S} \subseteq \Delta \times \mathrm{Q}$ with $\mathrm{S} \models \delta(q_n, \mathsf{v}(y))$ such that $x \cdot (d, q) \in \mathrm{R}$ for all $(d, q) \in \mathrm{S}$.

The acceptance condition allows us to say when a run is successful. Let R be a run of an Apt $\mathcal{M}$ on an input tree T and $u \in (\Delta \times \mathrm{Q})^\omega$ one of its branches. Let $\mathsf{inf}(u) \subseteq \mathrm{Q}$ denote the set of states that occur in infinitely many moves of u. Say that u *satisfies the parity acceptance condition* $\mathrm{F} = (\mathrm{F}_1, \ldots, \mathrm{F}_k)$ if the least index $i \in [1, k]$ for which $\mathsf{inf}(u) \cap \mathrm{F}_i \neq \emptyset$ is even. A run is *successful* if all its branches satisfy the parity acceptance condition F. An Apt *accepts* an input tree T iff there exists a successful run R of $\mathcal{M}$ on T.

The *language* $\mathrm{L}(\mathcal{M})$ of the Apt $\mathcal{M}$ is the set of trees T accepted by $\mathcal{M}$. Two automata are *equivalent* if they have the same language. The *emptiness problem* for alternating parity tree-automata is to decide, given $\mathcal{M}$, whether $\mathrm{L}(\mathcal{M}) = \emptyset$. The *universality problem* is to decide whether $\mathcal{M}$ accepts all trees.

3.1. From Logic to Automata

We reduce the model-checking problem of GradedSL to the emptiness problem for alternating parity tree automata [4]. The main step is to translate every GradedSL formula φ (i.e., φ may have free placeholders), arena $\mathcal{A}$, and state s, into an Apt that accepts a tree if and only if the tree encodes an assignment χ such that $\mathcal{A}, \chi, s \models \varphi$.

We first describe the encoding, following [4]. Informally, the arena $\mathcal{A}$ is encoded by its "tree-unwinding starting from s" whose nodes represent histories, i.e., the St-labeled St-tree $\mathsf{T} \triangleq \langle \text{Hst}(s), \mathsf{u} \rangle$ such that $\mathsf{u}(h)$ is the last symbol of h. Then, every strategy $\chi(e)$ with $e \in \mathsf{free}(\varphi)$ is encoded as an Ac-labelled tree over the unwinding. The unwinding and these strategies $\chi(e)$ are viewed as a single ($\text{Val} \times \text{St}$)-labeled tree where $\text{Val} \triangleq \mathsf{free}(\varphi) \to \text{Ac}$.

Definition 3.3. *The* encoding of χ (w.r.t. $\varphi, \mathcal{A}, s$) *is the* ($\text{Val} \times \text{St}$)*-labeled* St*-tree* $\mathsf{T} \triangleq \langle \text{T}, \mathsf{u} \rangle$ *such that* T *is the set of histories h of $\mathcal{A}$ starting with s and* $\mathsf{u}(h) \triangleq (\mathsf{f}, q)$ *where q is the last symbol in h and* $\mathsf{f} : \mathsf{free}(\varphi) \to \text{Ac}$ *is defined by* $\mathsf{f}(e) \triangleq \chi(e)(h)$ *for all* $e \in \mathsf{free}(\varphi)$.[7]

We now state and prove a lemma that says one can translate every formula in GradedSL into an APT. It is proved by induction on the structure of the formula φ, as in [4]. The idea for handling the new case, i.e., the graded quantifier $\langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g} \psi$, is to build an APT that is a projection of an APT that itself checks that each of the g tuples of strategies satisfies ψ and that each pair of g tuples is distinct. The case that $g \in \mathbb{N}$ directly builds the required automaton (as is done for SL [4]), while the case that $g \in \{\aleph_0, \aleph_1, 2^{\aleph_0}\}$ goes through logic. Write MSOL for monadic second-order logic in the signature of trees. We use the following two results that show how to express counting quantifiers in MSOL. The first is due to Rabin [40] and is nicely explained in [38].

Theorem 3.1 (MSOL and Automata). *For every MSOL formula $\alpha(Y)$ there exists an* Apt *accepting the set of trees Y such that $\alpha(Y)$ holds. Conversely, for every* Apt *there is an MSOL formula $\alpha(Y)$ that holds on those Y that are accepted by the* Apt*.*

The second is due to [41] and is proved using the composition technique.

Theorem 3.2. *For every MSOL formula $\alpha(\overline{X}, Y)$ and $\kappa \in \{\aleph_0, \aleph_1, 2^{\aleph_0}\}$ there exists an MSOL formula $\beta(\overline{X})$ equivalent to "there exist κ many trees Y such that $\alpha(\overline{X}, Y)$".*

Lemma 3.1. *For every* GradedSL *formula φ, arena $\mathcal{A}$, and state $s \in \text{St}$, there exists an* Apt *$\mathcal{M}$ such that for all assignments χ, if T is the encoding of χ (w.r.t. $\varphi, \mathcal{A}, s$), then $\mathcal{A}, \chi, s \models \varphi$ iff $\mathsf{T} \in \text{L}(\mathcal{M})$.*

Proof. As in [4] we induct on the structure of the formula φ to construct the corresponding automaton $\mathcal{M}$. The Boolean operations are easily dealt with using the fact that disjunction corresponds to non-determinism, and negation corresponds to dualising the automaton. The temporal operators are dealt with by following the unique play (determined by the given assignment) and verifying the required subformulas, e.g., for $\mathsf{X}\,\psi$ the automaton, after taking

[7] In case $\mathsf{free}(\varphi) = \emptyset$, then f is the (unique) empty function. In this case, the encoding of every χ may be viewed as the tree-unwinding from s.

one step along the play, launches a copy of the automaton for ψ. All of these operations incur a linear blowup in the size of the automaton. The only case that differs from SL is the quantification, i.e., we need to handle the case that $\varphi = \langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g}\psi$. Recall that $\mathcal{G}, \chi, s \models \langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g}\psi$ iff there exists g many tuples $\overline{\sigma_i}$ of strategies such that: $\overline{\sigma_a} \neq \overline{\sigma_b}$ for $a \neq b$, and $\mathcal{G}, \chi[\overline{x} \mapsto \overline{\sigma_i}], s \models \psi$ for $0 \leq i < g$.

There are two cases.

Case $g \in \{\aleph_0, \aleph_1, 2^{\aleph_0}\}$. Consider $\langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g}\psi$. By induction, there is an Apt $\mathcal{D}$ for ψ. Apply Theorem 3.1 to translate $\mathcal{D}$ into an MSOL formula α, then apply Theorem 3.2 to get an MSOL formula β that holds iff "there exist g many tuples of trees such that α" (recall that a tuple of trees is coded as a single tree). Finally, apply Theorem 3.1 to convert β into the required Apt.

Note that the blowup in the translations (MSOL to Apt, and closure under "there exists κ many trees") is non-elementary.

Case $g \in \mathbb{N}$. Let $\mathcal{M}$ be the Apt for ψ, given by induction. We show how to build an Npt for φ that mimics the definition of φ: it will be a projection of an Apt, which itself is the intersection of two automata, one checking that each of the g tuples of strategies satisfies ψ, and the other checking that each pair of the g tuples of strategies is distinct.

In more detail, introduce a set of fresh variables $X \triangleq \{x_i^j : i \leq n, j \leq g\}$, and consider the formulas ψ^j (for $j \leq g$) formed from ψ by renaming x_i (for $i \leq n$) to x_i^j. Define $\psi' \triangleq \wedge_{j \leq g}\psi^j$. Note that, by induction, each ψ^j has a corresponding Apt and thus, there is an Apt $\mathcal{B}_{\mathcal{M},X}$ for ψ' (conjunction can be dealt using universal-choice). Note that the input alphabet for $\mathcal{B}_{\mathcal{M},X}$ is $(\mathsf{free}(\psi') \to \mathrm{Ac}) \times \mathrm{St}$ and that $X \subseteq \mathsf{free}(\psi')$.

On the other hand, let $\mathcal{C}_X$ be an Apt with input alphabet $(\mathsf{free}(\psi') \to \mathrm{Ac}) \times \mathrm{St}$ that accepts a tree $\mathsf{T} = \langle \mathrm{T}, \mathsf{v} \rangle$ if and only if for every $a \neq b \leq g$ there exists $i \leq n$ and $h \in \mathrm{T}$ such that $\mathsf{v}(h) = (f, q)$ (where q is the last symbol of h) and $f(x_i^a) \neq f(x_i^b)$. To build $\mathcal{C}_X$ simply form the conjunction of automata $\mathcal{C}_X^{a,b}$ (for $a \neq b \leq g$), each of which is the disjunction of automata $\mathcal{C}_X^{a,b,i}$ (for $i \leq n$) that checks (by nondeterministically guessing a path) that there exists a history h starting in s such that $f(x_i^a) \neq f(x_i^b)$ (where the first co-ordinate of $\mathsf{v}(h)$ is f).

Form the Apt $\mathcal{D}_{\mathcal{M},X}$ for the intersection of $\mathcal{B}_{\mathcal{M},X}$ and $\mathcal{C}_X$ (formed using universal-choice).

Now, using the classic transformation [42], we remove alternation from the Apt $\mathcal{D}_{\mathcal{M},X}$ to get an equivalent Npt $\mathcal{N}$ (note that this step costs an exponential). Finally, use the fact that Npts are closed under projection (with no blowup) to get an Npt for the language $proj_X(L(\mathcal{N}))$ of trees that encode assignments χ satisfying φ.

For completeness we recall this last step. If L is a language of Σ-labeled trees with $\Sigma \triangleq \mathrm{A} \to \mathrm{B}$, and $X \subset \mathrm{A}$, then the X-*projection of* L, written $proj_{\mathrm{X}}(L)$, is the language of Σ'-labeled trees with $\Sigma' \triangleq \mathrm{A} \setminus \mathrm{X} \to \mathrm{B}$ such that $\mathsf{T} \triangleq \langle \mathrm{T}, \mathsf{v} \rangle \in proj_{\mathrm{X}}(L)$ if and only if there exists an X-labeled tree $\langle \mathrm{T}, \mathsf{w} \rangle$ such that the language L contains the tree $\langle \mathrm{T}, \mathsf{u} \rangle$ where $\mathsf{u} : \mathrm{T} \to (\mathrm{A} \to \mathrm{B})$ maps

$t \in \mathrm{T}$ to $\mathsf{v}(t) \cup \mathsf{w}(t)$. Now, if $\mathcal{N}$ is an NPT with input alphabet $\Sigma \triangleq \mathrm{A} \to \mathrm{B}$, and if $\mathrm{X} \subset \mathrm{A}$, then there is an NPT with input alphabet $\Sigma' \triangleq \mathrm{A} \setminus \mathrm{X} \to \mathrm{B}$ with language $proj_{\mathrm{X}}(L(\mathcal{N}))$.

The proof that the construction is correct is immediate. □

3.2. Decidability and Complexity of Model Checking

We can immediately conclude that model-checking graded strategy logic is decidable.

Theorem 3.3. *The model-checking problem for* GRADEDSL *is decidable. Moreover, the complexity is not bounded by any fixed tower of exponentials.*

Proof. For decidability, use Lemma 3.1 to transform the arena and φ into an APT and test its emptiness. The lower bound already holds for SL [4]. □

In the rest of this section we supply a finer analysis of the complexity of various fragments of graded strategy logic. To do this, we first analyse the number of states of the APT constructed in Lemma 3.1.

All the cases in the induction incur at most a linear blowup except for the quantification case. For the quantification case, in case $g \in \{\aleph_0, \aleph_1, 2^{\aleph_0}\}$ the blowup is non-elementary.

In case $g \in \mathbb{N}$ then the translation incurs an exponential blowup. Indeed, the number of states of the APT $\mathcal{B}_{\mathcal{M},X}$ is $g \times n$ times the number of states of the APT for ψ, and since $\mathcal{C}_X$ consists of the conjunction of $g(g-1)$ automata (one for each pair of tuples), and each such automaton has $O(n)$ many states, the number of states of $\mathcal{C}_X$ is $O(ng^2)$. Thus, the number of states of the APT $\mathcal{D}_{\mathcal{M},X}$ is polynomial in the number of states of the APT for ψ. Finally, the translation from an APT to an NPT results in an exponentially larger automaton [37].

In case all grades are from $\mathbb{N}$ and the formulas are written using the universal-strategy quantifier shorthand, we can easily modify the construction to handle quantifier-blocks in one shot as if they were a single quantifier, i.e., with a single exponential blowup. For instance, suppose $\phi = \langle\langle y_1, \ldots, y_m \rangle\rangle^{\geq h} \langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g} \psi$ (additional quantifiers are treated similarly). As in the proof, let $\mathcal{M}$ be the APT for ψ and take $\mathcal{D}_{\mathcal{M},X}$. Now, instead of immediately removing alternation and projecting, build $\mathcal{D}_{\mathcal{M}',Y}$ where $\mathcal{M}'$ is $\mathcal{D}_{\mathcal{M},X}$ and $Y \triangleq \{y_i^j : i \leq m, j \leq h\}$. Finally, remove alternation from $\mathcal{D}_{\mathcal{M}',Y}$ to get an NPT $\mathcal{N}'$, and then apply the $(X \cup Y)$-projection to the language of $\mathcal{N}'$ to get the desired APT for ϕ. Note that the size of $\mathcal{D}_{\mathcal{M}',Y}$ is exponential in the number of states of $\mathcal{M}$ since the costly step of removing alternation is performed only once. Similarly, to deal with a block of universal strategy quantifiers simply use dualisation. For instance, to deal with $\phi = [\![y_1, \ldots, y_m]\!]^{<h} [\![x_1, \ldots, x_n]\!]^{<g} \psi$ apply the previous procedure to the equivalent formula $\neg\langle\langle y_1, \ldots, y_m \rangle\rangle^{\geq h} \langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g} \neg\psi$ (recall that negating an APT is done by dualisation, which incurs no blowup).

Recall that GRADED$_{\mathbb{N}}$SL denotes the fragment of GRADEDSL in which all grades are restricted to $\mathbb{N}$.

Theorem 3.4.

1. *For every $k \geq 1$, the model-checking problem for* GRADED$_\mathbb{N}$SL *formulas of quantifer-block rank at most k is in* $(k+1)$EXPTIME.
2. *For every $k \geq 1$, the model-checking problem for* GRADED$_\mathbb{N}$SL *formulas of the form $\varphi = \wp\psi$, where $\wp$ is a quantifier-block of φ and ψ is of quantifier-block rank at most $k-1$, is in k*EXPTIME.
3. *The model-checking problem for* GRADED$_\mathbb{N}$SL *formulas of the form $\langle\langle x_1, \ldots, x_n\rangle\rangle^{\geq g}\psi$ or $[[x_1, \ldots, x_n]]^{<g}\psi$ is in* EXPTIME *w.r.t. the parameter g (written in unary).*

Proof. Before proving the upper bounds, recall that the complexity of checking emptiness (resp. universality) of an APT is in EXPTIME in the number of states [37].

For item 1 proceed as follows. As discussed after Lemma 3.1, for the case that all grades are in $\mathbb{N}$, the number of states of the APT for φ is a tower of exponentials whose height is the quantifier-block rank of φ. This gives the $(k+1)$EXPTIME bound.

For item 2 suppose that $\varphi = \wp\psi$ where $\wp$ consists of, say, n existential quantifiers (resp. universal quantifiers). The quantifier-block rank of ψ is $k-1$. Moreover, the APT $\mathcal{D}_\psi$, whose number of states is non-elementary in $k-1$, has the property that it is non-empty (resp. universal) if and only if the arena satisfies $\wp\psi$. Conclude that model checking $\wp\psi$ can be solved in kEXPTIME.

For item 3 first observe that the size of the APT constructed in Lemma 3.1 grows quadratically in g. The statement follows by recalling that the complexity of model-checking formulas of this form is exponential in the number of states of the APT. □

Theorem 3.5. *For every $k \geq 1$, the model-checking problem for* GRADED$_\mathbb{N}$SL[NG] *formulas of alternation number at most k is in* $(k+1)$EXPTIME *and* kEXPSPACE-*hard.*

Proof. The lower bound already holds for SL[NG] [4]. For the upper bound, as for SL[NG], note that principal formulas are "state formulas", i.e., their truth value only depends on the state in which they are interpreted (this is because they have no free placeholders). Thus, one can apply the following marking algorithm to a formula Φ. For every principal subformula $\varphi = \wp\psi$ of Φ for which ψ is quantifier-free, and for every state s of $\mathcal{A}$, introduce a new atomic proposition p_φ. Label s by p_φ (i.e., extend the labelling function at s to include p_φ) iff $\mathcal{A}, s \models \varphi$. Replace the subformula φ of Φ by the atom p_φ, and repeat this process. Observe that the complexity of marking a state is in $(k+1)$EXPTIME where $k = \mathsf{alt}(\varphi)$ (indeed, $\mathsf{alt}(\varphi) = \mathsf{qbr}(\varphi)$ since $\varphi = \wp\psi$ and ψ is quantifier-free, and thus one can apply Theorem 3.4 item 1). Also, the cost of the whole marking algorithm is the sum of the costs of all the marking rounds, and the number of rounds is at most the size of the formula. After the marking algorithm has completed, one is left with a Boolean combination of atomic propositions which is trivial to evaluate at each state. Thus the total time is at most $(k+1)$ExpTime. □

Theorem 3.6. *The model-checking problem for* Graded$_{\mathbb{N}}$SL[1g] *is* 2ExpTime-complete.

Proof. The lower-bound already holds for SL[1g] [4]. The upper-bound follows the same algorithm as for SL[1g] [4] but uses the (no more complex) construction from Lemma 3.1 for the strategic quantifier $\langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq g}$ instead of $\langle\langle x \rangle\rangle$. □

Finally, since model checking ATL* is 2ExpTime-hard, and ATL* is a syntactic fragment of Graded$_{\mathbb{N}}$ATL*, which itself is a syntactic fragment of Graded$_{\mathbb{N}}$SL[1g], we have that:

Theorem 3.7. *The model-checking problem for* Graded$_{\mathbb{N}}$ATL* *is* 2ExpTime-complete.

4. Analysing Games using GradedSL

In this section we describe how to use the models and formulas of GradedSL to reason about solution concepts from game theory. In particular, we show how to use arenas to model games of finite or infinite duration, and GradedSL to express the uniqueness of winning strategies, Nash equilibria, subgame-perfect equilibria, and Pareto-efficient profiles. We prove that deciding the uniqueness for all these solution concepts is not more expensive than merely deciding their existence, i.e., 2ExpTime. We note that while the problem of deciding the existence of, e.g., NE, is 2ExpTime-hard [7], it is not known whether deciding the uniqueness of NE is as hard. This intruiging question remains open, and we reserve it for future work.

4.1. Strategic Form and Infinitely Repeated Games

The *Strategic Form* is the most familiar representation of strategic interactions in Game Theory. A game written in this way amounts to a representation of every player's preference for every state of the world, in the special case where states of the world depend only on the players' combined actions.

Definition 4.1. *A* strategic form game *is a tuple* $(N, A, (\preceq_i)_{i \in N})$*, where:*

- *N is a finite set of n players, indexed by i;*
- *$A = A_1 \times \ldots \times A_n$, where A_i is a finite set of actions available to player i. Each vector $a = (a_1, \ldots, a_n) \in A$ is called an action profile;*
- *each $\preceq_i$ is a total pre-order (i.e., reflexive and transitive) on A.*

Note that a common way to give the preference relation is by using a *payoff function pay* : $A \to \mathbb{R}$, which assigns a real number to every element in A. In this case, the preference relation $\preceq_i$ is defined by having $a \preceq_i a'$ iff $pay(a) \leq pay(a')$.

A classic way to model players that repeatedly interact with each other in a game $(N, A, (\preceq_i)_{i \in N})$ is by *infinitely repeated games*, see e.g., [43]. We will illustrate by formalising an iterated prisoner's dilemma (Section 4.3).

	C	D
C	$-1, -1$	$-4, 0$
D	$0, -4$	$-3, -3$

Figure 1: Prisoner's Dilemma in Strategic Form. Each row corresponds to a possible action for player 1, each column corresponds to a possible action for player 2, and each cell corresponds to one possible outcome. Payoffs of the players for an outcome are written in the corresponding cell, with the payoff of player 1 listed first.

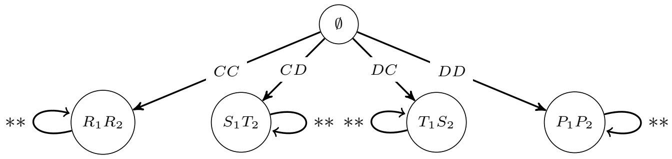

Figure 2: Arena of the Prisoner's dilemma.

4.2. Quasi-Quantitative Games and Objective-LTL *Games*

As expected, we can also specify games by arenas and a payoff function on plays. In this section we define quasi-quantitative games, a generalisation of *objective*-LTL *games* [8].

Let $\mathcal{A}$ be an arena with n agents. Let $m \in \mathbb{N}$, for each agent $\alpha_i \in \text{Ag}$, a *quasi-quantitative objective* is a tuple $S_i \triangleq \langle \mathsf{f}_i, L_i^1, \ldots, L_i^m \rangle$, where $\mathsf{f}_i : \{0,1\}^m \to \mathbb{Z}$, and each L_i^j is a set of sequences of sets of atomic propositions. If π is an infinite path, then agent α_i receives payoff $\mathsf{f}_i(b_i^\pi) \in \mathbb{N}$ where the j'th bit of b_i^π is 1 if and only if $\mathsf{ap}(\pi) \in L_i^j$. We assume agents are trying to maximise their payoffs. The tuple $\mathcal{G} = \langle \mathcal{A}, S_1, \ldots, S_n \rangle$ is called a *quasi-quantitative game.* In case each $f_i : \{0,1\}^m \to \{-1,1\}$ we say that the game is *win/lose.* If $\sum_{1 \leq i \leq n} \mathsf{f}_i(b_i^\pi) = 0$ for all π, then $\mathcal{G}$ is *zero-sum*, otherwise it is a *non zero-sum.*

In case each L_i^j is the set of models of an LTL formula φ_i^j over AP, we call $\mathcal{G}$ an *objective*-LTL *game.* We introduce the following useful shorthand. For $\alpha_i \in \text{Ag}$ and $a \in \{0,1\}^m$, define η_i^a for the LTL formula $\bigwedge_{j \leq m} \psi_{a,j}$ where $\psi_{a,j} = \varphi_i^j$ if $a_j = 1$ and $\psi_{a,j} = \neg\varphi_i^j$ if $a_j = 0$.

4.3. Example: The Prisoner's Dilemma (PD)

A natural way to draw games in strategic form is via an n-dimensional matrix. Figure 1 contains the matrix of the classic Prisoner's Dilemma. The two actions are C (co-operate) and D (defect). The payoffs are the prison sentences (in years) that the prisoners get for each pair of actions that they choose.[8] The dilemma faced by the prisoners is that, whatever the choice of the other prisoner, each is better off playing action D. But the result obtained when both play action D is worse than if they both play action C. Observe that the actual numbers are not important for there to be a dilemma. Rather, it is enough that the induced preference relation is $\mathbf{T}_i > \mathbf{R}_i > \mathbf{P}_i > \mathbf{S}_i$, where $\mathbf{R}_i$ represents the *reward* that player i receives if both cooperate; $\mathbf{P}_i$ is the *punishment* that player i receives if both defect; $\mathbf{T}_i$ is the *temptation* that player i receives as a sole defector, and $\mathbf{S}_i$ is the *sucker* payoff that player i receives as a sole cooperator.

We can model the Prisoner's Dilemma with the arena in Figure 2. Agent α_i (representing player i) has objective $S_i \triangleq \langle \mathsf{f}_i, \varphi_i^1, \varphi_i^2, \varphi_i^3, \varphi_i^4 \rangle$ where $\varphi_i^1 \triangleq \mathsf{X}\,\mathbf{S}_i$, $\varphi_i^2 \triangleq \mathsf{X}\,\mathbf{P}_i$, $\varphi_i^3 \triangleq \mathsf{X}\,\mathbf{R}_i$, and $\varphi_i^4 \triangleq \mathsf{X}\,\mathbf{T}_i$ and f_i returns the value of its input vector interpreted as a binary number, *e.g.*, $\mathsf{f}_i(0100) = 4$ that represents the payoff in which φ_i^3 is true. In words, we have two agents α_1 and α_2. Each agent has two actions, C and D. For each possible pair of moves, the game goes in a state whose atomic propositions represent the preferences.

It is well known that in the Prisoner's Dilemma the only Nash equilibrium is for both players to defect. The reason is that each prisoner must hedge against the possibility of the other one defecting. However, it is clear that if they would have both cooperated, they would be better off. If there was a way for one prisoner to later punish a defection of the other prisoner, it may not have to hedge, and would be able to cooperate instead. Such behaviours emerge as a rational choice, for example, when one considers the infinitely repeated prisoner's dilemma, in which the prisoners repeat the basic strategic form game infinitely often.[9] Indeed, it is well known that for this iterated game (for example, with a payoff that is the mean-payoff of the prison sentences [44]), a new Nash equilibrium emerges, in which both players use the so called *Grim* strategy, in which a prisoner cooperates as long as the other prisoner cooperates, but switches to always defect the first time the other prisoner defects. Observe that the resulting infinite play of this Nash equilibrium has both players cooperating all the time. The core reason that the pair of grim strategies is a Nash equilibrium for the mean-payoff version of the iterated prisoner's dilemma is that this payoff ignores the price of being a 'sucker' on any finite prefix of the play, i.e., that the mean-payoff of a play is independent of any finite prefix of that play — other properties of the mean are not needed, and constitute unimportant noise. Indeed, the same Nash equilibria would emerge if, for example, one takes instead

[8] The story behind the dilemma is this: Two people have been arrested for robbing a bank and placed in separate isolation cells. Each has two possible choices, remaining silent (action C) or confessing (action D). If a robber confesses and the other remains silent, the former is released and the latter stays in prison for a long time. If both confess they are both convicted, but will get early parole. If both remain silent, they get a lighter sentence (e.g., on firearms possession charges).

[9] Alternatively, one can introduce the threat of a punishment for defecting by considering a probabilistic version in which it is unclear to the prisoners how many repetitions will be used. Note, however, that a fixed number of repetitions turns out to be essentially the same as playing only once [44].

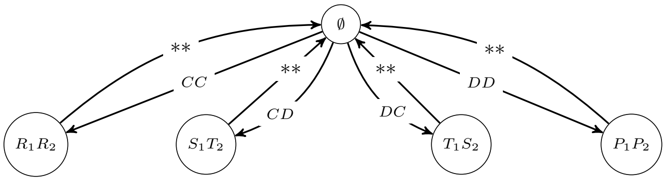

Figure 3: Arena of the Iterated Prisoner's dilemma.

of the mean-payoff the maximal payoff that repeats infinitely often.

More generally, given a game in strategic form, and a preference relation $\preceq_i$ over its set of possible outcomes A, one can define a new preference relation $\preceq_i^\infty$ over A^ω by assigning a payoff to every subset of A and assigning to each play the set $inf(\pi) \subseteq A$ of outcomes in A that appear infinitely often in π. Formally, let $F_i : 2^A \to \mathbb{Z}$ be a function mapping subsets of A to integers, and define $\pi \preceq_i^\infty \pi'$ iff $F_i(inf(\pi)) \leq F_i(inf(\pi'))$.[10] For example, for the iterated prisoners' dilemma, setting $F_i(X)$ to be the number of elements y in A such that $y \prec_i x$ where x is a $\preceq_i$-maximal element of X, results in a game with the same set of Nash equilibria as in the mean payoff version.

We formalise the infinitely repeated prisoner's dilemma as an objective-LTL game. The arena is in Figure 3. The preferences, for agent α_i, are defined by the objective $S_i \triangleq \langle \mathsf{f}_i, \varphi_i^1, \varphi_i^2, \varphi_i^3, \varphi_i^4 \rangle$ where $\varphi_i^1 \triangleq \mathsf{G}\,\mathsf{F}\,\mathbf{S}_i$, $\varphi_i^2 \triangleq \mathsf{G}\,\mathsf{F}\,\mathbf{P}_i$, $\varphi_i^3 \triangleq \mathsf{G}\,\mathsf{F}\,\mathbf{R}_i$, and $\varphi_i^4 \triangleq \mathsf{G}\,\mathsf{F}\,\mathbf{T}_i$, and f_i as before.

4.4. Illustrating GradedSL*: uniqueness of solutions*

We illustrate how to express with GradedSL some important solution concepts in Game Theory. We start with the concept of winning strategy that is useful in zero-sum games, and then we analyse the well known solution concepts, such as Nash and subgame-perfect equilibria, that are used in non zero-sum games. We use ordinary SL quantifiers (i.e., $\langle\!\langle x \rangle\!\rangle, [\![x]\!]$) since, as observed in Section 2, these are expressible in GradedSL.

4.4.1. Winning strategies

In two-agent win-lose zero-sum games the main solution concept is the *winning strategy.* That is, if G is such an objective-LTL game, then a strategy for agent α_1 is *winning* if and only if for all strategies of agent α_2, the resulting induced play has payoff 1 for agent α_1. This can be expressed in SL as follows:

$$\phi_{WS}(x) \triangleq [\![y]\!](\alpha_1, x)(\alpha_2, y) \bigvee_{f_1(a)=1} \eta_1^a$$

where η_1^a is the LTL formula defined in Section 4.2. Thus, the following formula expresses that there is a unique winning strategy for agent α_1:

$$\langle\!\langle x \rangle\!\rangle^{\geq 1} \phi_{WS}(x) \wedge \neg \langle\!\langle x \rangle\!\rangle^{\geq 2} \phi_{WS}(x) \qquad (1)$$

[10] This is reminiscent of the Muller acceptance condition in automata theory.

Observe that this is a formula of GRADED$_{\mathbb{N}}$SL[NG] of alternation number 1. Thus, by Theorem 3.4 we get:

Theorem 4.1. *Deciding if a given agent in a two-agent zero-sum objective-*LTL *game has a unique winning strategy can be solved in* 2EXPTIME.

We illustrate with an example. In [45] the authors describe a two-agent game named "Cop and the Robber", played in a maze, in which the objective of the Robber is to reach an exit (and thus the objective of the Cop is to ensure the Robber never reaches the exit). The authors describe two closely related mazes in which the Robber has, respectively, exactly one and exactly two winning strategies. Both these properties can easily be expressed by GRADEDSL. For instance, the Robber has a single LTL objective $\mathsf{F}\, exit$, and the following formula of GRADED$_{\mathbb{N}}$SL expresses that the Robber has exactly one winning strategy:

$$\langle\langle x \rangle\rangle^{\geq 1} [[y]] (\text{Robber}, x)(\text{Cop}, y)\, \mathsf{F}\, exit \wedge \neg \langle\langle x \rangle\rangle^{\geq 2} [[y]] (\text{Robber}, x)(\text{Cop}, y)\, \mathsf{F}\, exit.$$

4.4.2. Nash Equilibria

The central solution concept in non zero-sum games is the Nash Equilibrium. A tuple of strategies, one for each agent, is called a *strategy profile.* A strategy profile is a *Nash equilibrium (NE)* if no agent can increase his payoff by unilaterally choosing a different strategy. A game may have zero, one, or many NE.

Consider the case that each agent α_i has a general objective tuple $S_i \triangleq \langle \mathsf{f}_i, \varphi_i^1, \ldots, \varphi_i^m \rangle$. Recall the definition of the LTL formulas η_i^a from Section 4.2.

For $\overline{x} \triangleq (x_1 \ldots x_n)$ and $\overline{y} \triangleq (y_1 \ldots y_n)$, the following formula says that if all agents follow $\overline{x}$, then no agent i gets a better payoff by deviating and following y_i:

$$\phi_{DEV}(\overline{x}, \overline{y}) \triangleq \bigwedge_{i=1}^{n} \bigwedge_{a \in \{0,1\}^m} (\flat(\overline{x}/y_i)\eta_i^a) \rightarrow \bigvee_{\mathsf{f}_i(a') \geq \mathsf{f}_i(a)} \flat(\overline{x})\eta_i^{a'}$$

where $\flat(\overline{x}) = (\alpha_1, x_1) \ldots (\alpha_n, x_n)$, and

$$\flat(\overline{x}/y_i) = (\alpha_1, x_1) \ldots (\alpha_{i-1}, x_{i-1})(\alpha_i, y_i)(\alpha_{i+1}, x_{i+1}) \ldots (\alpha_n, x_n).$$

Then, the following SL formula says that $\overline{x}$ is a NE

$$\phi_{NE}(\overline{x}) \triangleq [[y_1]] \ldots [[y_n]] \phi_{DEV}(\overline{x}, \overline{y}),$$

and the following GRADED$_{\mathbb{N}}$SL[NG] formula expresses that there is a unique NE:

$$\langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq 1} [[y_1]] \ldots [[y_n]] \phi_{DEV}(\overline{x}, \overline{y}) \wedge \neg \langle\langle x_1, \ldots, x_n \rangle\rangle^{\geq 2} [[y_1]] \ldots [[y_n]] \phi_{DEV}(\overline{x}, \overline{y})$$

Thus, by Theorem 3.4 we get:

Theorem 4.2. *Deciding if an objective-*LTL *game has a unique NE can be solved in* 2EXPTIME.

Rational synthesis can be formalised as the problem of deciding if a given game has a NE such that the resulting play satisfies a given LTL formula Ψ. In our setting, we get the following result by replacing ϕ_{DEV} by $\Psi \wedge \phi_{DEV}$ in the previous formula:

Theorem 4.3. *Deciding if an objective-*LTL *game has a unique NE satisfying an* LTL *formula* Ψ *can be solved in* 2ExpTime.

4.4.3. Pareto efficiency

A strategy profile is said to be *Pareto efficient (PE)* if there is no other strategy profile that makes some agent better off without making another agent worse off. The formula $\phi_{PE}(\overline{x}) \triangleq [\![x'_1]\!] \ldots [\![x'_n]\!] \psi(\overline{x}, \overline{x'})$ expresses that $\overline{x}$ is PE where $\psi(\overline{x}, \overline{x'})$ is

$$\bigwedge_{i \leq n} \bigwedge_{(a,a') \in X_i} \left((\flat(\overline{x})\eta_i^a \wedge \flat(\overline{x'})\eta_i^{a'}) \rightarrow \bigvee_{j \neq i} \bigvee_{(c,c') \in Y_i} (\flat(\overline{x})\eta_j^c \wedge \flat(\overline{x'})\eta_j^{c'}) \right),$$

where $(a, a') \in X_i$ iff $\mathsf{f}_i(a') > \mathsf{f}_i(a)$, where $(c, c') \in Y_i$ iff $\mathsf{f}_j(c') < \mathsf{f}_j(c)$, $\flat(\overline{x}) \triangleq (\alpha_1, x_1) \ldots (\alpha_n, x_n)$, and $\flat(\overline{x'}) \triangleq (\alpha_1, x'_1) \ldots (\alpha_n, x'_n)$. Using graded modalities, we can thus express that there is a unique PE using the following Graded$_{\mathbb{N}}$SL[ng] formula of alternation number 1:

$$\langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq 1} \phi_{PE}(\overline{x}) \wedge \neg \langle\!\langle x_1, \ldots, x_n \rangle\!\rangle^{\geq 2} \phi_{PE}(\overline{x}).$$

Thus, by using Theorem 3.4 we get:

Theorem 4.4. *Deciding if an objective-*LTL *game has a unique Pareto efficient profile can be solved in* 2ExpTime.

4.4.4. Subgame-perfect equilibria

Finally, we end with a discussion of the problem of deciding if a game has a unique subgame-perfect equilibrium, and give an upper bound. It has been argued (in [46, 8]) that NE may be implausible when used for sequential games (of which infinitely repeating games are central examples), and that a more robust notion is subgame-perfect equilibrium [47].

Informally, a strategy profile is a subgame-perfect equilibrium if it is a NE in every reachable subgame. Here is the mathematical definition instantiated for quasi-quantitative games (following the definition in [43] for extensive-form games). Given a history $h \in \mathrm{Hst}(s_I)$ ending in state s, say $h = us$, and a strategy $\sigma \in \mathrm{Str}(s_I)$, the *h-translation* of σ is the strategy $\sigma_{|h} \in \mathrm{Str}(s)$ that maps $h' \in \mathrm{Hst}(s)$ to $\sigma(u \cdot h')$. Given a quasi-quantitative game $\mathcal{G} = \langle \mathcal{A}, S_1, \ldots, S_n \rangle$, the profile $\sigma_1, \ldots, \sigma_n$ is a *subgame-perfect equilibrium (SPE)* iff for all histories $h \in \mathrm{Hst}(s_I)$, the profile $\sigma_{1|h}, \ldots, \sigma_{n|h}$ is a NE in $\mathcal{G} = \langle \mathcal{A}_{|h}, S_{1|h}, \ldots, S_{n|h} \rangle$ where $\mathcal{A}_{|h}$ is the same arena as $\mathcal{A}$ but with s as the initial state, and if $S = \langle \mathsf{f}_i, L_i^1, \ldots, L_i^m \rangle$ then $S_{|h} = \langle \mathsf{f}_i, H_i^1, \ldots, H_i^m \rangle$ where $\pi \in H_i^j$ iff $u \cdot \pi \in L_i^j$. The point is that the payoff in $\mathcal{G}_{|h}$ applies to the whole path (i.e., starting from s_I), even though the strategies only apply after h.

Using the notation in the previous paragraph, suppose each L_i^j is prefix-independent, i.e., $\pi \in L_i^j$ iff $\pi_{\geq n} \in L_i^j$ for all $n \geq 1$ (here $\pi_{\geq n}$ is the suffix of π starting at position n). In this case, $H_i^j = L_i^j$. Observe that the assumption that the objectives are prefix-independent is not too restrictive. Indeed, as discussed in Section 4.3, in many infinitely repeated games the outcome ignores all finite prefixes of the play.

Thus, suppose $\mathcal{G}$ is an objective-LTL game in which the set of models of each φ_i^j is prefix-independent. The following formula of SL expresses that $\overline{x}$ is an SPE:[11]

$$\phi_S(\overline{x}) \triangleq [\![z_1]\!] \dots [\![z_n]\!][\![y_1]\!] \dots [\![y_n]\!](\alpha_1, z_1) \dots (\alpha_n, z_n)\, \mathsf{G}\, \phi_{DEV}(\overline{x}, \overline{y}).$$

Indeed, since $[\![\,\cdot\,]\!]$ commutes with G, the formula $\phi_S(\overline{x})$ is equivalent to

$$[\![z_1]\!] \dots [\![z_n]\!](\alpha_1, z_1) \dots (\alpha_n, z_n)\, \mathsf{G}\, \phi_{NE}(\overline{x}),$$

which is true in $\mathcal{A}, \chi, s_I$ iff for all histories h starting in s_I and ending, say, in state s, we have that $\mathcal{A}, \chi', s \models \phi_{NE}$ where the strategy $\chi'(x)$ is the h-translation of the strategy $\chi(x)$, i.e., the profile $\chi'(x_1), \dots, \chi'(x_n)$ is a NE in $\mathcal{G}_{|h}$.

Using graded modalities, we can thus express there is a unique SPE (assuming each φ_i^j is prefix-independent) as the following $\textsc{Graded}_{\mathbb{N}}\text{SL}[\textsc{ng}]$ formula of alternation number 1:

$$\langle\!\langle x_1, \dots, x_n \rangle\!\rangle^{\geq 1} \phi_S(\overline{x}) \wedge \neg \langle\!\langle x_1, \dots, x_n \rangle\!\rangle^{\geq 2} \phi_S(\overline{x}).$$

Thus, by using Theorem 3.4 we get:

Theorem 4.5. *Deciding if an objective-*LTL *game with prefix-independent objectives φ_i^j has a unique SPE can be solved in* 2ExpTime.

5. Conclusion

The Nash equilibrium is the foundational solution concept in game theory. The last twenty years have witnessed the introduction of many logical formalisms for modeling and reasoning about solution concepts, and NE in particular [3, 4, 6, 48, 49, 9, 7]. These formalisms are useful for addressing qualitative questions such as *"does the game admit a Nash equilibrium?"*. Among others, Strategy Logic (SL) has come to the fore as a general formalism that can express and solve this question, for LTL objectives, in 2ExpTime. Contrast this with the fact that this question is 2ExpTime-complete even for two player zero-sum LTL games [50].

One of the most important questions about NE in computational game theory is *"does the game admit more than one NE?"* [14, 15] This issue has

[11] Previous formalisations of SPE overlook the need for a condition like prefix-independence [46, 4, 8].

been deeply investigated in game theory and is shown to be very challenging [16, 17, 18, 13, 19, 51, 52, 53]. Prior to this work, no logic-based technique, as far as we know, solved the corresponding decision problem, i.e., whether or not a given game has a unique NE.[12]

In this paper we introduced GradedSL to address and solve the unique NE problem. We have demonstrated that GradedSL is elegant, simple, and very powerful, and can solve the unique NE problem for LTL objectives in 2ExpTime, and thus at the same complexity that is required to merely decide if a NE exists. We also illustrated that one can express the uniqueness of other solution concepts, including winning strategies, subgame-perfect equilibria, and Pareto-efficient profiles, all in 2ExpTime. We remark that the exact complexity of the existence of a unique NE, and of counting the number of NE, has been studied for other representations of games, notably games in strategic form with rational co-efficients and considering mixed strategies [55, 56]. The exact complexity of the existence of NE in our representation is currently unknown. Finally, our work gives the first algorithmic solution to the model-checking problem of a graded variant of ATL*, and proves it to be 2ExpTime-complete.

In the multi-agent setting, reasoning about epistemic alternatives plays a key role. Thus, an important extension would be to combine the knowledge operators in SLK [57] with the graded quantifiers we introduced for GradedSL. Since strategic reasoning under imperfect information has an undecidable model-checking problem [58], one may restrict to memoryless strategies as was done for SLK. More involved, would be to add grades to the knowledge operators, thus being able to express “there exists at least g equivalent worlds” [59].

Finally, another direction is to implement GradedSL and its model-checking procedure in a formal verification tool. A reasonable approach would be, for example, to extend the tool SLK-MCMAS [57, 60].

Acknowledgments

We thank Michael Wooldridge for pointing out the importance of uniqueness of Nash Equilibria in game theory. Benjamin Aminof is supported by the Austrian National Research Network S11403-N23 (RiSE) of the Austrian Science Fund (FWF) and by the Vienna Science and Technology Fund (WWTF) through grant ICT12-059. Sasha Rubin is supported by a Marie Curie fellowship of the Istituto Nazionale di Alta Matematica. Aniello Murano is partially supported by the GNCS 2016 project: Logica, Automi e Giochi per Sistemi Auto-adattivi.

[12] In the related work section we discussed the logic GSL [26, 54] that, although motivated by the need to address the unique NE problem, only supplies a model-checking algorithm for a very small fragment of GSL that cannot express LTL goals and, it is assumed, is not able to express the existence of NE.

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