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───── **Abstract** ─────

The window mechanism, introduced by Chatterjee et al. [17] for mean-payoff and total-payoff objectives in two-player turn-based games on graphs, refines long-term objectives with time bounds. This mechanism has proven useful in a variety of settings [14, 12], and most recently in timed systems [30].

In the timed setting, the so-called fixed timed window parity objectives have been studied. A fixed timed window parity objective is defined with respect to some time bound and requires that, at all times, we witness a time frame, i.e., a window, of size less than the fixed bound in which the smallest priority is even. In this work, we focus on the bounded timed window parity objective. Such an objective is satisfied if there exists some bound for which the fixed objective is satisfied. The satisfaction of bounded objectives is robust to modeling choices such as constants appearing in constraints, unlike fixed objectives, for which the choice of constants may affect the satisfaction for a given bound.

We show that verification of bounded timed window objectives in timed automata can be performed in polynomial space, and that timed games with these objectives can be solved in exponential time, even for multi-objective extensions. This matches the complexity classes of the fixed case. We also provide a comparison of the different variants of window parity objectives.

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1 Introduction

Real-time systems. *Timed automata* [2] are a means of modeling systems in which the passage of time is critical. A timed automaton is a finite automaton extended with a set of *real-valued* variables called *clocks*. All clocks of a timed automaton increase at the same rate and measure the elapse of time in a continuous fashion. Clocks constrain transitions in timed automata and can be reset on these transitions.

Timed automata provide a formal setting for the verification of real-time systems [2, 4]. When analyzing timed automata, we usually exclude some unrealistic behaviors. More precisely, we ignore *time-convergent paths*, i.e., infinite paths in which the total elapsed time is bounded. Even though timed automata induce uncountable transition systems, many properties can be checked using the *region abstraction*, a finite quotient of the transition system.

Timed automata can also be used to design correct-by-construction controllers for real-time systems. To this end, we model the interaction of the system and its uncontrollable environment as a timed automaton game [31], or more simply a *timed game*. A timed game

is a two-player game played on a timed automaton by the system and its environment for an infinite number of rounds. At each round, both players propose a real-valued delay and an action, and the play progresses following the fastest move.

The notion of winning in a timed game must take time-convergence in account; following [23], we declare as winning the plays that are either *time-divergent and satisfy the objective of the player*, or that are *time-convergent and the player is not responsible for convergence.*

Parity conditions.   Parity conditions are a canonical way of specifying ω-regular conditions, such as safety and liveness. A parity objective is defined from a priority function, which assigns a non-negative integer to each location of a timed automaton. The *parity objective* requires that the smallest priority witnessed infinitely often is even.

The window mechanism.   A parity objective requires that for all odd priorities seen infinitely often, there is some smaller even priority seen infinitely often. However, the parity objective does not enforce timing constraints; the parity objective can be satisfied despite there being arbitrarily large delays between odd priorities and smaller even priorities. Such behaviors may be undesirable, e.g., if odd priorities model requests in a system and even priorities model responses.

The window mechanism was introduced by Chatterjee et al. for mean-payoff games in graphs [17] and later applied to parity games in graphs [14] and mean-payoff and parity objectives in Markov decision processes [12]. It is a means of reinforcing the parity objective with *timing constraints*. A *direct fixed timed window parity objective* for some fixed time bound requires that at all times, we witness a *good window*, i.e., a time frame of size less than the fixed bound in which the smallest priority is even. In other words, this objective requires that the parity objective be locally satisfied at all times, where the notion of locality is fixed in the definition. This window parity objective and a prefix-independent variant requiring good windows from some point on were studied in [30].

The main focus of this article is another variant of timed window parity objectives called *direct bounded timed window parity objectives*, which extend the bounded window parity objectives of [14]. This objective is satisfied if and only if there exists some time bound for which the direct fixed objective is satisfied. While this objective also requires that the parity objective be locally satisfied at all times, the notion of locality is *not fixed a priori*. In particular, unlike the fixed objective, its satisfaction is robust to modeling choices such as the choice of constants constraining transitions, and depends only on the high-level behavior of the system being modeled. In addition to this direct objective, we also consider a prefix-independent variant, the *bounded timed window parity objective*, which requires that some suffix satisfies a direct bounded objective.

Contributions.   We study conjunctions of (respectively direct) bounded timed window parity objectives in the setting of timed automata and of timed games. We show that checking that all time-divergent paths of a timed automaton satisfy a conjunction of (respectively direct) bounded timed window parity objectives can be done in PSPACE (Theorem 13). We also show that if all time-divergent paths of a timed automaton satisfy a (respectively direct) bounded timed window parity objective, then there exists a bound for which the corresponding fixed objective is satisfied (Corollaries 8 and 10).

In timed games, we show that in the direct case, the set of winning states can be computed in EXPTIME (Theorem 18) by means of a timed game with an ω-regular request-response

objective [37, 19]. We show that, assuming a global clock that cannot be reset, finite-memory strategies suffice to win, and if a winning strategy for a direct bounded objective exists, there exists a finite-memory winning strategy that is also winning for a direct fixed objective (Theorem 17). In the prefix-independent case, we provide a fixed-point algorithm to compute the set of winning states that runs in EXPTIME (Theorem 23). We infer from the correctness proof that, assuming a global clock, finite-memory strategies suffice for winning and if a winning strategy exists, then there exists a finite-memory winning strategy that is also winning for some fixed objective (Theorem 22).

We complement all membership results above with lower bounds and establish PSPACE-completeness for timed automata-related problems and EXPTIME-completeness for timed games-related problems (Theorem 24).

Comparison. Window objectives strengthen classical objectives with timing constraints; they provide *conservative approximations* of these objectives (e.g., [17, 14, 12]). The complexity of window objectives, comparatively to that of the related classical objective, depends on whether one considers a single-objective or multi-objective setting. In turn-based games on graphs, window objectives provide *polynomial-time* alternatives to the classical objectives [17, 14] in the single-objective setting, despite, e.g., turn-based parity games on graphs not being known to be solvable in polynomial time (parity games were recently shown to be solvable in quasi-polynomial time [16]). On the other hand, in the multi-objective setting, the complexity is higher than that of the classical objectives; for instance, solving a turn-based game with a conjunction of fixed (respectively bounded) window parity objectives is EXPTIME-complete [14], whereas solving games with conjunctions of parity objectives is co-NP complete [20]. In the timed setting, we establish that solving timed games with conjunctions of bounded timed window parity objectives is EXPTIME-complete, i.e., dense time comes for free, similarly to the fixed case in timed games [30].

Timed games with classical parity objectives can be solved in exponential time [23, 22], i.e., the complexity class of solving timed games with window parity objectives matches that of solving timed games with classical parity objectives. Timed games with parity objectives can be solved by means of a reduction to an untimed parity game played on a graph polynomial in the size of the region abstraction and the number of priorities [22]. However, most algorithms for games on graphs with parity objectives suffer from a blow-up in complexity due to the number of priorities. Timed window parity objectives provide an alternative to parity objectives that bypasses this blow-up; in particular, we show in this paper that *timed games with a single bounded timed window objective can be solved in time polynomial in the size of the region abstraction and the number of priorities*.

In timed games, we show that winning for a (respectively direct) bounded timed window parity objective is equivalent to winning for a (respectively direct) fixed timed window parity objective with some sufficiently large bound that depends on the number of priorities, number of objectives and the size of the region abstraction. Despite the fact that this bound can be directly computed (Theorems 17 and 22), solving timed games with (respectively direct) fixed timed window parity objectives for a certain bound takes time that is polynomial in the size of the region abstraction, the number of priorities and the *fixed bound*. This bound may be large; the algorithms we provide for timed games with (respectively direct) bounded timed window parity objectives avoid this additional contribution to the complexity.

Related work. The window mechanism has seen numerous extensions in addition to the previously mentioned works, e.g., [5, 3, 11, 15, 28, 35, 8]. Window parity objectives, especially

bounded variants, are closely related to the notion of finitary ω-regular games, e.g., [18], and the semantics of PROMPT-LTL [29]. The window mechanism can be used to ensure a certain form of (local) guarantee over paths; different techniques have been considered in stochastic models [10, 13, 7]. Timed automata have numerous extensions, e.g., hybrid systems (e.g., [9] and references therein) and probabilistic timed automata (e.g., [32]); the window mechanism could prove useful in these richer settings. Finally, we recall that game models provide a framework for the synthesis of correct-by-construction controllers [34].

Outline.   Section 2 presents all preliminary notions. Window objectives, relations between them and a useful property of bounded window objectives are presented in Section 3. The verification of bounded window objectives in timed automata is studied in Section 4. Section 5 presents algorithms for timed games with bounded window objectives. Lower bounds for completeness of the verification and realizability problems for bounded window objectives are provided in Section 6. Finally, in Section 7, we compare the untimed and timed settings, and the fixed and bounded objectives. Appendix A expands upon the preliminaries and discusses winning strategies in timed games with ω-regular objectives.

2   Preliminaries

Notation.   We denote the set of non-negative real numbers by $\mathbb{R}_{\geq 0}$, and the set of non-negative integers by $\mathbb{N}$. Given some non-negative real number x, we write $\lfloor x \rfloor$ for the integral part of x and $\mathsf{frac}(x) = x - \lfloor x \rfloor$ for its fractional part. Given two sets A and B, we let 2^A denote the power set of A and A^B denote the section of functions $B \to A$.

Timed automata.   A clock variable, or *clock*, is a real-valued variable. Let C be a set of clocks. A *clock constraint* over C is a conjunction of formulae of the form $x \sim c$ with $x \in C$, $c \in \mathbb{N}$, and $\sim \in \{\leq, \geq, >, <\}$. We write $x = c$ as shorthand for the clock constraint $x \geq c \wedge x \leq c$. Let $\Phi(C)$ denote the set of clock constraints over C.

We refer to functions $v \in \mathbb{R}_{\geq 0}^C$ as *clock valuations* over C. A clock valuation v over a set C of clocks satisfies a clock constraint of the form $x \sim c$ if $v(x) \sim c$ and v satisfies a conjunction $g \wedge h$ of two clock constraints g and h if it satisfies both g and h. Given a clock constraint g and clock valuation v, we write $v \models g$ if v satisfies g.

For a clock valuation v and $\delta \geq 0$, we let $v + \delta$ be the valuation defined by $(v + \delta)(x) = v(x) + \delta$ for all $x \in C$. For any valuation v and $D \subseteq C$, we define $\mathsf{reset}_D(v)$ to be the valuation agreeing with v for clocks in $C \setminus D$ and that assigns 0 to clocks in D. We denote by $\mathbf{0}^C$ the zero valuation, assigning 0 to all clocks in C.

A *timed automaton* (TA) is a tuple $(L, \ell_{\mathsf{init}}, C, \Sigma, I, E)$ where L is a finite set of *locations*, $\ell_{\mathsf{init}} \in L$ is an initial location, C a finite set of *clocks* containing a special clock γ which keeps track of the total time elapsed, Σ a finite set of actions, $I \colon L \to \Phi(C)$ an *invariant* assignment function and $E \subseteq L \times \Phi(C) \times \Sigma \times 2^{C \setminus \{\gamma\}} \times L$ a finite edge relation. We only consider deterministic timed automata, i.e., we assume that in any location ℓ, there are no two different outgoing edges $(\ell, g_1, a, D_1, \ell_1)$ and $(\ell, g_2, a, D_2, \ell_2)$ sharing the same action such that the conjunction $g_1 \wedge g_2$ is satisfiable. For an edge (ℓ, g, a, D, ℓ'), the clock constraint g is called the *guard* of the edge.

A TA $\mathcal{A} = (L, \ell_{\mathsf{init}}, C, \Sigma, I, E)$ gives rise to an uncountable transition system $\mathcal{T}(\mathcal{A}) = (S, s_{\mathsf{init}}, M, \to)$ with the state space $S = L \times \mathbb{R}_{\geq 0}^C$, the initial state $s_{\mathsf{init}} = (\ell_{\mathsf{init}}, \mathbf{0}^C)$, set of transition system actions $M = \mathbb{R}_{\geq 0} \times (\Sigma \cup \{\bot\})$ and the transition relation $\to \subseteq S \times M \times S$ defined as follows: for any action $a \in \Sigma$ and delay $\delta \geq 0$, we have that $((\ell, v), (\delta, a), (\ell', v')) \in$

$\rightarrow$ if and only if there is some edge $(\ell, g, a, D, \ell') \in E$ such that $v + \delta \models g$, $v' = \mathsf{reset}_D(v + \delta)$, $v + \delta \models I(\ell)$ and $v' \models I(\ell')$; for any delay $\delta \geq 0$, $((\ell, v)(\delta, \bot), (\ell, v + \delta)) \in \rightarrow$ if $v + \delta \models I(\ell)$. Let us note that the satisfaction set of clock constraints is convex: it is described by a conjunction of inequalities. Whenever $v \models I(\ell)$, the above condition $v + \delta \models I(\ell)$ (the invariant holds after the delay) is equivalent to requiring $v + \delta' \models I(\ell)$ for all $0 \leq \delta' \leq \delta$ (the invariant holds at each intermediate time step).

A *move* is any pair in $\mathbb{R}_{\geq 0} \times (\Sigma \cup \{\bot\})$ (i.e., an action in the transition system). For any move $m = (\delta, a)$ and states s, $s' \in S$, we write $s \xrightarrow{m} s'$ or $s \xrightarrow{\delta, a} s'$ as shorthand for $(s, m, s') \in \rightarrow$. Moves of the form $(\delta, \bot)$ are called *delay moves*. For any move $m = (\delta, a)$, we let $\mathsf{delay}(m) = \delta$. We say a move m is enabled in a state s if there is some s' such that $s \xrightarrow{m} s'$. There is at most one successor per move in a state, as we do not allow two guards on edges labeled by the same action to be simultaneously satisfied.

A *path* in a TA $\mathcal{A}$ is a finite or infinite sequence $s_0 m_0 s_1 \ldots \in S(MS)^* \cup (SM)^\omega$ such that for all $j \in \mathbb{N}$, s_j is a state of $\mathcal{T}(\mathcal{A})$ and $s_j \xrightarrow{m_j} s_{j+1}$ is a transition in $\mathcal{T}(\mathcal{A})$. A path is *initial* if $s_0 = s_{\mathsf{init}}$. For clarity, we write $s_0 \xrightarrow{m_0} s_1 \xrightarrow{m_1} \cdots$ instead of $s_0 m_0 s_1 \ldots$.

A state s is said to be *reachable from a state s'* if there exists a path from s' to s. Similarly, a set of states $T \subseteq S$ is said to be reachable from some state s' if there is a path from s' to a state in T. We say that a state is *reachable* if it is reachable from the initial state.

An infinite path $\pi = (\ell_0, v_0) \xrightarrow{m_0} (\ell_1, v_1) \xrightarrow{m_1} \ldots$ is *time-divergent* if the sequence $(v_j(\gamma))_{j \in \mathbb{N}}$ is not bounded from above. A path that is not time-divergent is called *time-convergent*; time-convergent paths are traditionally ignored in analysis of timed automata [1, 2] as they model unrealistic behavior. This includes ignoring *Zeno paths*, which are time-convergent paths along which infinitely many actions appear.

Regions.   The transition system induced by a TA is infinite. Qualitative properties of TAs can nonetheless be analyzed using the region abstraction [2], a quotient of the transition system by an equivalence relation of finite index. Fix a TA $\mathcal{A} = (L, \ell_{\mathsf{init}}, C, \Sigma, I, E)$. For each clock $x \in C$, let c_x denote the largest constant to which x is compared to in guards and invariants of $\mathcal{A}$.

We define an equivalence relation over clock valuations of C: we say that two clock valuations v and v' over C are *clock-equivalent* for $\mathcal{A}$, denoted by $v \equiv_{\mathcal{A}} v'$, if the following properties are satisfied: (i) for all clocks $x \in C$, $v(x) > c_x$ if and only if $v'(x) > c_x$; (ii) for all clocks $x \in \{z \in C \mid v(z) \leq c_z\}$, $\lfloor v(x) \rfloor = \lfloor v'(x) \rfloor$; (iii) for all clocks $x, y \in \{z \in C \mid v(z) \leq c_z\} \cup \{\gamma\}$, $v(x) \in \mathbb{N}$ if and only if $v'(x) \in \mathbb{N}$, and $\mathsf{frac}(v(x)) \leq \mathsf{frac}(v(y))$ if and only if $\mathsf{frac}(v'(x)) \leq \mathsf{frac}(v'(y))$. When $\mathcal{A}$ is clear from the context, we say that two valuations are clock-equivalent rather than clock-equivalent for $\mathcal{A}$.

An equivalence class for this relation is referred to as a *clock region*. We denote the equivalence class for $\equiv_{\mathcal{A}}$ of a clock valuation v as $[v]$. We let Reg denote the set of all clock regions. The number of clock regions is finite, and exponential in the number of clocks and the encoding of the constants c_x, $x \in C$. More precisely, we have the bound $|\mathsf{Reg}| \leq |C|! \cdot 2^{|C|} \cdot \prod_{x \in C}(2c_x + 1)$.

We extend the equivalence defined above to states as well. We say that two states $s = (\ell, v)$ and $s' = (\ell', v')$ are *state-equivalent*, denoted $s \equiv_{\mathcal{A}} s'$, whenever $\ell = \ell'$ and $v \equiv_{\mathcal{A}} v'$. An equivalence class for this relation is referred to as a *state region*. Given some state $s \in S$, we write $[s]$ for its equivalence class. We identify the set of state regions with the set $L \times \mathsf{Reg}$ and sometimes denote state regions as pairs $(\ell, R) \in L \times \mathsf{Reg}$ in the sequel.

The satisfaction of clock constraints that appear in $\mathcal{A}$ is uniform inside of a clock region. For a clock region $R \in \mathsf{Reg}$ and a clock constraint g of $\mathcal{A}$, we write $R \models g$ to denote

that $v \models g$ for some $v \in R$. This does not hold for arbitrary clock constraints, e.g., it does not hold for clock constraints involving constants larger than those in $\mathcal{A}$. The reset operator also respects regions, in the sense that for any clock valuation v and $D \subseteq C$, $[\mathsf{reset}_D(v)] = \{\mathsf{reset}_D(v') \mid v' \in [v]\}$. Let R, R' be two clock regions. We say that R' is a *successor region* of R if for all valuations $v \in R$, there exists some delay $\delta_v \geq 0$ such that $v + \delta_v \in R'$.

We now have all of the notions required to define the region abstraction of $\mathcal{T}(\mathcal{A})$. The *region abstraction* of $\mathcal{T}(\mathcal{A})$ is the finite transition system $(L \times \mathsf{Reg}, [s_{\mathsf{init}}], \{\tau\}, \rightarrow')$ where $L \times \mathsf{Reg}$ is the state space, elements of which are state regions, with the state region of the initial state as its initial state, a unique move τ (we abstract the actions of the TA away), and a transition relation $\rightarrow'$ defined as follows. For any two state regions (ℓ, R), $(\ell', R') \in L \times \mathsf{Reg}$, $(\ell, R) \xrightarrow{\tau}' (\ell', R')$ holds if and only if one of the two following conditions hold: (i) there exists some edge $(\ell, g, a, D, \ell') \in E$ and some successor region R_{succ} of R such that $R_{\mathsf{succ}} \models g \wedge I(\ell)$, $R' = \{\mathsf{reset}_D(v) \mid v \in R_{\mathsf{succ}}\}$ and $R' \models I(\ell')$, or (ii) $\ell = \ell'$ and R' is a successor region of R such that $R' \models I(\ell)$. These conditions respectively abstract transitions that use edges and delay transitions in $\mathcal{T}(\mathcal{A})$.

Any (finite or infinite) path $s_0 \xrightarrow{m_0} s_1 \xrightarrow{m_1} \ldots$ of $\mathcal{T}(\mathcal{A})$ induces a path $[s_0] \xrightarrow{\tau}' [s_1] \xrightarrow{\tau}' \ldots$ in the region abstraction. Conversely, for any path $(\ell_0, R_0) \xrightarrow{\tau}' (\ell_1, R_1) \xrightarrow{\tau}' \ldots$ and any $v_0 \in R_0$, one can find a path of $\mathcal{T}(\mathcal{A})$ $(\ell_0, v_0) \xrightarrow{m_0} (\ell_1, v_1) \xrightarrow{m_1} \ldots$ such that $v_n \in R_n$ for all $n \in \mathbb{N}$. Due to this relation between paths, qualitative properties that depend only on locations or regions can be verified using the region abstraction.

Priorities.   A *priority function* is a function $p \colon L \rightarrow \{0, \ldots, \mathsf{D} - 1\}$ with $\mathsf{D} \leq |L| + 1$. We use priority functions to express parity objectives. A K-*dimensional priority function* is a function $p \colon L \rightarrow \{0, \ldots, \mathsf{D} - 1\}^{\mathsf{K}}$ which assigns vectors of priorities to locations. Given a K-dimensional priority function p and a dimension $k \in \{1, \ldots, \mathsf{K}\}$, we write p_k for the priority function given by p on dimension k.

Timed games.   We consider two player games played on TAs. We refer to the players as player 1 ($\mathcal{P}_1$) for the system and player 2 ($\mathcal{P}_2$) for the environment. We use the notion of timed automaton games of [23].

A *timed* (automaton) *game* (TG) is a tuple $\mathcal{G} = (\mathcal{A}, \Sigma_1, \Sigma_2)$ where $\mathcal{A} = (L, \ell_{\mathsf{init}}, C, \Sigma, I, E)$ is a TA and (Σ_1, Σ_2) is a partition of Σ. We refer to actions in Σ_i as $\mathcal{P}_i$ actions for $i \in \{1, 2\}$.

Recall that a move is a pair $(\delta, a) \in \mathbb{R}_{\geq 0} \times (\Sigma \cup \{\bot\})$. Let S denote the set of states of $\mathcal{T}(\mathcal{A})$. In each state $s = (\ell, v) \in S$, the moves available to $\mathcal{P}_1$ are the elements of the set $M_1(s)$ where

$$M_1(s) = \left\{ (\delta, a) \in \mathbb{R}_{\geq 0} \times (\Sigma_1 \cup \{\bot\}) \mid \exists s', s \xrightarrow{\delta, a} s' \right\}$$

contains moves with $\mathcal{P}_1$ actions and delay moves that are enabled in s. The set $M_2(s)$ is defined analogously with $\mathcal{P}_2$ actions. We write M_1 and M_2 for the set of all moves of $\mathcal{P}_1$ and $\mathcal{P}_2$ respectively.

At each state s along a play, both players simultaneously select a move $m^{(1)} \in M_1(s)$ and $m^{(2)} \in M_2(s)$. Intuitively, the fastest player gets to act and in case of a tie, the move is chosen non-deterministically. This is formalized by the *joint destination function*

$\mathsf{JD} : S \times M_1 \times M_2 \to 2^S$, defined by

$$
\mathsf{JD}(s, m^{(1)}, m^{(2)}) = \begin{cases} \{s' \in S \mid s \xrightarrow{m^{(1)}} s'\} & \text{if } \mathsf{delay}(m^{(1)}) < \mathsf{delay}(m^{(2)}) \\ \{s' \in S \mid s \xrightarrow{m^{(2)}} s'\} & \text{if } \mathsf{delay}(m^{(1)}) > \mathsf{delay}(m^{(2)}) \\ \{s' \in S \mid s \xrightarrow{m^{(i)}} s', i = 1, 2\} & \text{if } \mathsf{delay}(m^{(1)}) = \mathsf{delay}(m^{(2)}). \end{cases}
$$

For $m^{(1)} = (\delta^{(1)}, a^{(1)}) \in M_1$ and $m^{(2)} = (\delta^{(2)}, a^{(2)}) \in M_2$, we write $\mathsf{delay}(m^{(1)}, m^{(2)}) = \min\{\delta^{(1)}, \delta^{(2)}\}$ to denote the delay occurring when $\mathcal{P}_1$ and $\mathcal{P}_2$ play $m^{(1)}$ and $m^{(2)}$ respectively.

A play is defined similarly to an infinite path: a *play* is an infinite sequence of the form $s_0(m_0^{(1)}, m_0^{(2)})s_1(m_1^{(1)}, m_1^{(2)}) \ldots \in (S(M_1 \times M_2))^\omega$ where for all indices $j \in \mathbb{N}$, $m_j^{(i)} \in M_i(s_j)$ for $i \in \{1, 2\}$ and $s_{j+1} \in \mathsf{JD}(s_{j+1}, m_{j+1}^{(1)}, m_{j+1}^{(2)})$. A *history* is a finite prefix of a play ending in a state. A play or history $s_0(m_0^{(1)}, m_0^{(2)})s_1 \ldots$ is *initial* if $s_0 = s_{\mathsf{init}}$. For any history $h = s_0(m_0^{(1)}, m_0^{(2)}) \ldots (m_{n-1}^{(1)}, m_{n-1}^{(2)})s_n$, we set $\mathsf{last}(h) = s_n$. For a play $\pi = s_0(m_0^{(1)}, m_0^{(2)})s_1 \ldots$, we write $\pi_{|n} = s_0(m_0^{(1)}, m_0^{(2)}) \ldots (m_{n-1}^{(1)}, m_{n-1}^{(2)})s_n$. Plays of $\mathcal{G}$ follow paths of $\mathcal{A}$. For a play, there may be several such paths: if at some point of the play both players use a move with the same delay and successor state, either move can label the transition in a matching path.

Similarly to paths, a play $\pi = (\ell_0, v_0)(m_0^{(1)}, m_0^{(2)}) \cdots$ is *time-divergent* if and only if $(v_j(\gamma))_{j \in \mathbb{N}}$ is not bounded from above. Otherwise, we say a play is *time-convergent*. We define the following sets: $\mathsf{Plays}(\mathcal{G})$ for the set of plays of $\mathcal{G}$; $\mathsf{Hist}(\mathcal{G})$ for the set of histories of $\mathcal{G}$; $\mathsf{Plays}_\infty(\mathcal{G})$ for the set of time-divergent plays of $\mathcal{G}$. We also write $\mathsf{Plays}(\mathcal{G}, s)$ to denote plays starting in state s of $\mathcal{T}(\mathcal{A})$.

We will deal with objectives that require properties in the limit. For this purpose, we introduce a notation for suffixes of plays. For any $n \in \mathbb{N}$ and any play $\pi = s_0(m_0^{(1)}, m_0^{(2)})s_1 \ldots \in \mathsf{Plays}(\mathcal{G})$, we let $\pi_{n\to} = s_n(m_n^{(1)}, m_n^{(2)})s_{n+1} \ldots$ denote the suffix of π starting at index n.

Strategies. A *strategy* for $\mathcal{P}_i$ is a function describing which move a player should use based on a history. Formally, a strategy for $\mathcal{P}_i$ is a function $\sigma_i \colon \mathsf{Hist}(\mathcal{G}) \to M_i$ such that for all $\pi \in \mathsf{Hist}(\mathcal{G})$, $\sigma_i(\pi) \in M_i(\mathsf{last}(\pi))$. This last condition requires that each move given by a strategy be enabled in the last state of a play.

A play or history $s_0(m_0^{(1)}, m_0^{(2)})s_1 \ldots$ is said to be consistent with a $\mathcal{P}_i$-strategy σ_i if for all indices j, $m_j^{(i)} = \sigma_i(\pi_{|j})$. Given a $\mathcal{P}_i$ strategy σ_i, we define $\mathsf{Outcome}_i(\sigma_i)$ (resp. $\mathsf{Outcome}_i(\sigma_i, s)$) to be the set of plays (resp. set of plays starting in state s) consistent with σ_i.

In general, strategies can exploit full knowledge of the past, and need not admit some finite representation. In the sequel, we focus on a subclass of finite-memory strategies. A strategy is a finite-memory strategy if it can be encoded by a finite Mealy machine, i.e., a deterministic automaton with outputs. A *Mealy machine* (for a strategy of $\mathcal{P}_1$) is a tuple $\mathcal{M} = (\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}}, \alpha_{\mathsf{mov}})$ where $\mathfrak{M}$ is a finite set of states, $\mathfrak{m}_{\mathsf{init}} \in \mathfrak{M}$ is an initial state, $\alpha_{\mathsf{up}} \colon \mathfrak{M} \times S \to \mathfrak{M}$ is the memory update function and $\alpha_{\mathsf{mov}} \colon \mathfrak{M} \times S \to M_1$ is the next-move function.

Let $\mathcal{M} = (\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}}, \alpha_{\mathsf{mov}})$ be a Mealy machine. We define the strategy induced by $\mathcal{M}$ as follows. Let ε denote the empty word. We first define the iterated update function $\alpha_{\mathsf{up}}^* \colon S^* \to \mathfrak{M}$ inductively as $\alpha_{\mathsf{up}}^*(\varepsilon) = \mathfrak{m}_{\mathsf{init}}$ and for any $s_0 \ldots s_n \in S^*$, we let $\alpha_{\mathsf{up}}^*(s_0 \ldots s_n) = \alpha_{\mathsf{up}}(\alpha_{\mathsf{up}}^*(s_0 \ldots s_{n-1}), s_n)$. The strategy σ induced by $\mathcal{M}$ is defined by $\sigma(h) = \alpha_{\mathsf{mov}}(\alpha_{\mathsf{up}}^*(s_0 \ldots s_{n-1}), s_n)$ for any history $h = s_0(m_0^{(1)}, m_0^{(2)}) \ldots (m_{n-1}^{(1)}, m_{n-1}^{(2)})s_n \in \mathsf{Hist}(\mathcal{G})$. A strategy σ is said to be *finite-memory* if it is induced by some Mealy machine.

We will exploit a subclass of finite-memory strategies that are well-behaved with respect to regions. We say that some strategy σ is a finite-memory region strategy if it can be encoded by a Mealy machine the updates of which depend only on the current region (rather than the state itself) and such that, in a given memory state, the moves proposed in two state-equivalent game states traverse the same state regions during the proposed delay and then move to the same region. Formally, a strategy is a *finite-memory region strategy* it is induced by some Mealy machine $\mathcal{M} = (\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}}, \alpha_{\mathsf{mov}})$ where for any memory states $\mathfrak{m} \in \mathfrak{M}$ and any two state-equivalent states $s = (\ell, v)$, $s' = (\ell', v') \in S$, $\alpha_{\mathsf{up}}(\mathfrak{m}, s) = \alpha_{\mathsf{up}}(\mathfrak{m}, s')$ and the moves $(\delta, a) = \alpha_{\mathsf{mov}}(\mathfrak{m}, s)$ and $(\delta', a') = \alpha_{\mathsf{mov}}(\mathfrak{m}, s')$ are such that $a = a'$, $[v + \delta] = [v' + \delta']$ and $\{[v + \delta_{\mathsf{mid}}] \mid 0 \le \delta_{\mathsf{mid}} \le \delta\} = \{[v' + \delta_{\mathsf{mid}}] \mid 0 \le \delta_{\mathsf{mid}} \le \delta'\}$. We view the update function of Mealy machines inducing finite-memory region strategies as functions $\alpha_{\mathsf{up}} : \mathfrak{M} \times L \times \mathsf{Reg} \to \mathfrak{M}$.

Objectives.   An objective represents the property we desire on paths of a TA or a goal of a player in a TG. Formally, we define an *objective* as a set $\Psi \subseteq S^\omega$ of infinite sequences of states. An objective Ψ is a *region objective* if given two sequences of states $s_0 s_1 \ldots, s_0' s_1' \ldots \in S^\omega$ such that for all $j \in \mathbb{N}$, $s_j \equiv_{\mathcal{A}} s_j'$, we have $s_0 s_1 \ldots \in \Psi$ if and only if $s_0' s_1' \ldots \in \Psi$. Intuitively, the satisfaction of a region objective depends only on the witnessed sequence of state regions.

An ω-regular region objective is a region objective recognized by some deterministic parity automaton. A (total) *deterministic parity automaton* (DPA) is a tuple $H = (Q, q_{\mathsf{init}}, A, \mathsf{up}, p)$, where Q is a finite set of states, $q_{\mathsf{init}} \in Q$ is the initial state, A is a finite alphabet, $\mathsf{up} : Q \times A \to Q$ is a total transition function and $p : Q \to \{0, \ldots, \mathsf{D} - 1\}$ is a priority function over the states of the DPA.

Let $w = a_0 a_1 \ldots \in A^\omega$ be an infinite word. The execution of H over w is the infinite sequence of states $q_0 q_1 \ldots \in Q^\omega$ that starts in the initial state of H, i.e., $q_0 = q_{\mathsf{init}}$ and such that for all $n \in \mathbb{N}$, $q_{n+1} = \mathsf{up}(q_n, a_n)$, i.e., each step of the execution is performed by reading a letter of the input word. An infinite word $w \in A^\omega$ is accepted by H if the smallest priority appearing infinitely often along the execution $q_0 q_1 \ldots \in Q^\omega$ over w is even, i.e. if $(\liminf_{n \to \infty} p(q_i)) \bmod 2 = 0$. We denote by $\mathcal{L}(H)$ the set of words accepted by H.

We use DPAs to encode ω-regular objectives over state regions. A DPA $H = (Q, q_{\mathsf{init}}, L \times \mathsf{Reg}, \mathsf{up}, p)$ formally encodes the objective $\{s_0 s_1 \ldots \in S^\omega \mid [s_0][s_1] \ldots \in \mathcal{L}(H)\}$.

In the sequel, we use the following ω-regular region objectives in addition to the window objectives studied in this work. The window objectives we consider later on are derived from the parity objective. The *parity* objective for a one-dimensional priority function $p : L \to \{0, \ldots, \mathsf{D} - 1\}$ requires that the smallest priority seen infinitely often is even. Formally, we define $\mathsf{Parity}(p) = \{(\ell_0, v_0)(\ell_1, v_1) \ldots \in S^\omega \mid (\liminf_{n \to \infty} p(\ell_n)) \bmod 2 = 0\}$. For hardness arguments, we rely on safety objectives. A *safety* objective, defined with respect to a set of locations $F \subseteq L$, requires that no location in F be visited. Formally, the safety objective for F is defined as $\mathsf{Safe}(F) = \{(\ell_0, v_0)(\ell_1, v_1) \ldots \in S^\omega \mid \forall n, \ell_n \notin F\}$.

For the sake of brevity, given some path $\pi = s_0 m_0 s_1 \ldots$ of a TA or a play of a TG $\pi = s_0 (m_0^{(1)}, m_0^{(2)}) s_1 \ldots$ and an objective $\Psi \subseteq S^\omega$, we write $\pi \in \Psi$ to mean that the sequence of states $s_0 s_1 \ldots$ underlying π is in Ψ, and say that π satisfies the objective Ψ.

Winning conditions.   In games, we distinguish objectives and *winning conditions*. We adopt the definition of [23]. Let Ψ be an objective. It is desirable to have victory be achieved in a physically meaningful way: for example, it is unrealistic to have a safety objective be achieved by stopping time. This motivates a restriction to time-divergent plays. However, this requires $\mathcal{P}_1$ to force the divergence of plays, which is not reasonable, as $\mathcal{P}_2$ can stall using delays with zero time units. Thus we also declare winning time-convergent plays where

$\mathcal{P}_1$ is *blameless*. Let $\mathsf{Blameless}_1$ denote the set of $\mathcal{P}_1$-blameless plays, which we define in the following way.

Let $\pi = s_0(m_0^{(1)}, m_0^{(2)})s_1 \ldots$ be a play or a history. We say $\mathcal{P}_1$ is *not responsible* (or not to be blamed) for the transition at step k in π if either $\delta_k^{(2)} < \delta_k^{(1)}$ ($\mathcal{P}_2$ is faster) or $\delta_k^{(1)} = \delta_k^{(2)}$ and $s_k \xrightarrow{\delta_k^{(1)}, a_k^{(1)}} s_{k+1}$ does not hold in $\mathcal{T}(\mathcal{A})$ ($\mathcal{P}_2$'s move was selected and did not have the same target state as $\mathcal{P}_1$'s) where $m_k^{(i)} = (\delta_k^{(i)}, a_k^{(i)})$ for $i \in \{1, 2\}$. The set $\mathsf{Blameless}_1$ is formally defined as the set of infinite plays π such that there is some j such that for all $k \geq j$, $\mathcal{P}_1$ is not responsible for the transition at step k in π.

Given an objective Ψ, we set the winning condition $\mathsf{WC}_1(\Psi)$ for $\mathcal{P}_1$ to be the set of plays

$$\mathsf{WC}_1(\Psi) = (\mathsf{Plays}(\mathcal{G}, \Psi) \cap \mathsf{Plays}_\infty(\mathcal{G})) \cup (\mathsf{Blameless}_1 \setminus \mathsf{Plays}_\infty(\mathcal{G})),$$

where $\mathsf{Plays}(\mathcal{G}, \Psi) = \{\pi \in \mathsf{Plays}(\mathcal{G}) \mid \pi \in \Psi\}$. Winning conditions for $\mathcal{P}_2$ are defined by exchanging the roles of the players in the former definition.

We consider that the two players are adversaries and have opposite objectives, Ψ and $S^\omega \setminus \Psi$. Let us note that $\mathsf{WC}_1(\Psi) \cup \mathsf{WC}_2(S^\omega \setminus \Psi) \neq \mathsf{Plays}(\mathcal{G})$. While this union subsumes all time-divergent plays and time-convergent plays that are blameless for one player, it omits the time-convergent plays that are blameless for neither player.

A *winning strategy* for $\mathcal{P}_i$ for an objective Ψ from a state s_0 is a strategy σ_i such that $\mathsf{Outcome}_i(\sigma_i, s_0) \subseteq \mathsf{WC}_i(\Psi)$. We say that a state is winning for $\mathcal{P}_1$ for an objective Ψ if $\mathcal{P}_1$ has a winning strategy from this state.

Winning for ω-regular region objectives. Let us consider a DPA $H = (Q, q_{\mathsf{init}}, L \times \mathsf{Reg}, \mathsf{up}, p)$ with $p \colon Q \to \{0, \ldots, \mathsf{D} - 1\}$ specifying an ω-regular region objective in the TG $\mathcal{G}$. Let $\mathsf{D}' = \mathsf{D}$ if D is odd and $\mathsf{D}' = \mathsf{D} - 1$ otherwise. The set of winning states for the objective $\mathcal{L}(H)$ is a union of state regions and is computable in exponential time [24, 23].

▶ **Theorem 1.** *The set of winning states of $\mathcal{P}_1$ in the TG $\mathcal{G}$ for the objective given by H is a union of state regions and is computable in time $\mathcal{O}((4 \cdot |L| \cdot |\mathsf{Reg}| \cdot |Q| \cdot \mathsf{D})^{\mathsf{D}'+2})$.*

Furthermore, in TGs with ω-regular objectives, finite-memory region strategies suffice for winning. We can even obtain winning finite-memory region strategies for which all delays are bounded by some constant. Intuitively, if one replaces moves of $\mathcal{P}_1$ of a winning strategy by delay moves with durations that are bounded by some constant, one still has a winning strategy. The broad justification is any outcome of the modified finite-memory region strategy shares its sequence of states with an outcome of the original strategy obtained by having $\mathcal{P}_2$ interrupt the moves of $\mathcal{P}_1$ that have a large delay. We therefore have the following, which is elaborated upon in Appendix A.

▶ **Theorem 2.** *There exists a finite-memory region strategy with $2 \cdot |Q| \cdot \mathsf{D}$ states proposing delays of at most 1 that is winning for the objective specified by H from any state that is winning for $\mathcal{P}_1$.*

Decision problems. We consider two different problems for an objective Ψ. The first is the *verification problem* for Ψ, which asks given a TA whether all *time-divergent initial* paths satisfy the objective. Second is the *realizability problem* for Ψ, which asks whether in a TG, $\mathcal{P}_1$ has a winning strategy from the initial state.

3   Bounded window objectives

The main focus of this paper is a variant of timed window parity objectives called *bounded timed window parity objectives*. These are defined from the *fixed timed window parity objectives* studied in [30], where these are referred to as timed window parity objectives. The definitions of the different variants of timed window parity objectives are provided in Section 3.1. Section 3.2 presents the relationships between the different variants and the original parity objective. Finally, Section 3.3 introduces a technical result used to simplify paths and plays witnessing the violation of a bounded window objective.

For this entire section, we fix a TG $\mathcal{G} = (\mathcal{A}, \Sigma_1, \Sigma_2)$ where $\mathcal{A} = (L, \ell_{\mathsf{init}}, C, \Sigma_1 \cup \Sigma_2, I, E)$ and a one-dimensional priority function $p\colon L \to \{0, \ldots, \mathsf{D} - 1\}$.

3.1   Objective definitions

Fixed objectives.   Fixed window objectives depend on a fixed time bound $\lambda \in \mathbb{N}$. The first building block for the definition of window objectives is the notion of good window. A good window for the bound λ is intuitively a time interval of length strictly less than λ for which the smallest priority of the locations visited in the interval is even. We define the *timed good window (parity) objective* as the set of sequences of states that have a good window at their start. Formally, we define $\mathsf{TGW}(p, \lambda) = \big\{(\ell_0, v_0)(\ell_1, v_1)\ldots \in S^\omega \mid \exists n \in \mathbb{N}, \min_{0 \le j \le n} p(\ell_j) \bmod 2 = 0 \text{ and } v_n(\gamma) - v_0(\gamma) < \lambda\big\}$.

The *direct fixed timed window (parity) objective* for the bound λ, denoted by $\mathsf{DFTW}(p, \lambda)$, requires that the timed good window objective is satisfied by all suffixes of a sequence. Formally, we define $\mathsf{DFTW}(p, \lambda)$ as the set $\{s_0 s_1 \ldots \in S^\omega \mid \forall n \in \mathbb{N}, s_n s_{n+1} \ldots \in \mathsf{TGW}(p, \lambda)\}$.

Unlike the parity objective, $\mathsf{DFTW}(p, \lambda)$ is not prefix-independent. Therefore, a prefix-independent variant of the direct fixed timed window objective, the *fixed timed window (parity) objective* $\mathsf{FTW}(p, \lambda)$, was also studied in [30]. Formally, we define $\mathsf{FTW}(p, \lambda) = \{s_0 s_1 \ldots \in S^\omega \mid \exists n \in \mathbb{N}, s_n s_{n+1} \ldots \in \mathsf{DFTW}(p, \lambda)\}$.

Bounded objectives.   A sequence of states satisfies the (respectively direct) bounded timed window objective if there exists a time bound λ for which the sequence satisfies the (respectively direct) fixed timed window objective. Unlike the fixed case, this bound depends on the sequence of states, and need not be uniform, e.g., among all sequences of states induced by time-divergent paths of a TA or among all sequences of states induced by time-divergent outcomes of a strategy in a TG.

We formally define the *(respectively direct) bounded timed window (parity) objective* $\mathsf{BTW}(p)$ (respectively $\mathsf{DBTW}(p)$) as the set $\mathsf{BTW}(p) = \{s_0 s_1 \ldots \in S^\omega \mid \exists \lambda \in \mathbb{N}, s_0 s_1 \ldots \in \mathsf{FTW}(p, \lambda)\}$ (respectively $\mathsf{DBTW}(p) = \{s_0 s_1 \ldots \in S^\omega \mid \exists \lambda \in \mathbb{N}, s_0 s_1 \ldots \in \mathsf{DFTW}(p, \lambda)\}$). The objective $\mathsf{BTW}(p)$ is a prefix-independent variant of $\mathsf{DBTW}(p)$.

In the sequel, to distinguish the prefix-independent variants from direct objectives, we may refer to the fixed timed window or bounded timed window objectives as *indirect objectives*.

Multi-objective extensions.   In addition to the direct and indirect bounded objectives, we will also study some of their multi-objective extensions. More precisely, we assume for these definitions that p is a multi-dimensional priority function, i.e., $p\colon L \to \{0, \ldots, \mathsf{D} - 1\}^\mathsf{K}$, and define a multi-dimensional objective as the conjunction of the objectives derived from the component functions $p_1, \ldots, p_\mathsf{K}$.

Multi-dimensional extensions are referred to as generalized objectives. Formally, in the fixed case, for a bound $\lambda \in \mathbb{N}$, we define the *generalized direct fixed timed window objective*

as $\mathsf{GDFTW}(p, \lambda) = \bigcap_{1 \le k \le \mathsf{K}} \mathsf{DFTW}(p_k, \lambda)$ and the *generalized fixed timed window objective* as $\mathsf{GFTW}(p, \lambda) = \bigcap_{1 \le k \le \mathsf{K}} \mathsf{FTW}(p_k, \lambda)$. In the bounded case, we define the *generalized direct bounded timed window objective* as $\mathsf{GDBTW}(p) = \bigcap_{1 \le k \le \mathsf{K}} \mathsf{DBTW}(p_k)$ and the *generalized bounded timed window objective* as $\mathsf{GBTW}(p) = \bigcap_{1 \le k \le \mathsf{K}} \mathsf{BTW}(p_k)$.

3.2   Relationships between objectives

We discuss the relationships between the different timed window parity objectives and the parity objective in this section. We discuss both inclusions and differences between the different objectives.

The inclusions are induced by the fact that a direct objective is more restrictive than its prefix-independent counterpart, and similarly, by the fact that a fixed objective is more restrictive than its bounded counterpart. Parity objectives, on the other hand, are less restrictive than any of the timed window objectives, as they require no time-related aspect to hold.

▶ **Lemma 3.** *The following inclusions hold for any $\lambda \in \mathbb{N}$:*
- $\mathsf{DFTW}(p, \lambda) \subseteq \mathsf{FTW}(p, \lambda) \subseteq \mathsf{BTW}(p) \subseteq \mathsf{Parity}(p)$ *and*
- $\mathsf{DFTW}(p, \lambda) \subseteq \mathsf{DBTW}(p) \subseteq \mathsf{BTW}(p) \subseteq \mathsf{Parity}(p)$.

Proof. We only argue that $\mathsf{BTW}(p) \subseteq \mathsf{Parity}(p)$, as all other inclusions are straightforward. Let $\pi = s_0 s_1 \ldots \in \mathsf{BTW}(p)$. It follows that π has some suffix $\pi' = s_n s_{n+1} \ldots$ such that $\pi' \in \mathsf{DFTW}(p, \lambda)$ for some $\lambda \in \mathbb{N}$. Every suffix of π' satisfies $\mathsf{TGW}(p, \lambda)$. This implies that any odd priority in π' is followed by a smaller even priority. It follows that the smallest priority appearing infinitely often in π is even, as there are finitely many priorities. ◀

It can be shown that in some TAs, these inclusions may be strict. In other words, the relations presented in Lemma 3 are the most general relationships for timed window parity objectives. We use the TA used to show that fixed objectives are a strict refinement of parity objectives in [30] to exemplify this.

▶ **Lemma 4.** *There exists a TA in which all time-divergent paths satisfy the parity objective, all of the inclusions of Lemma 3 are strict and in which $\mathsf{FTW}(p, \lambda) \not\subseteq \mathsf{DBTW}(p)$ and $\mathsf{DBTW}(p) \not\subseteq \mathsf{FTW}(p, \lambda)$ hold for any value of λ.*

Proof. Consider the TA $\mathcal{B}$ depicted in Figure 1 and let $p_{\mathcal{B}}$ denote its priority function. It is easy to see that all time-divergent paths satisfy the parity objective: if the TA remains in location ℓ_1 after some point, letting time diverge, the only priority seen infinitely often is 2; if location ℓ_2 is visited infinitely often, the smallest priority seen infinitely often is 0.

We will only consider sequences of states induced by initial paths of $\mathcal{B}$ in the following arguments. We denote states by triples (ℓ, v, v') where $\ell \in \{\ell_0, \ell_1, \ell_2\}$ and v and v' respectively refer to the valuation of x and of γ. Let $\lambda \in \mathbb{N}$.

Let us first show that $\mathsf{DFTW}(p, \lambda) \subsetneq \mathsf{FTW}(p, \lambda)$, $\mathsf{DBTW}(p_{\mathcal{B}}) \subsetneq \mathsf{BTW}(p_{\mathcal{B}})$ and $\mathsf{FTW}(p, \lambda) \not\subseteq \mathsf{DBTW}(p_{\mathcal{B}})$ hold. Due to the inclusions of Lemma 3, it suffices to provide some sequence of states in $\mathsf{FTW}(p_{\mathcal{B}}, \lambda) \setminus \mathsf{DBTW}(p_{\mathcal{B}})$ to obtain these relations. For example, consider the sequence of states $(\ell_0, 0, 0)(\ell_1, 1, 1)(\ell_1, 2, 2) \ldots$ obtained by using action a in ℓ_0 after 1 time unit, and then letting time diverge by means of delay moves. The suffix $(\ell_1, 1, 1)(\ell_1, 2, 2) \ldots$ of this sequence satisfies $\mathsf{DFTW}(p_{\mathcal{B}}, \lambda)$: the only priority that appears in this suffix is even. Therefore the sequence $(\ell_0, 0, 0)(\ell_1, 1, 1)(\ell_1, 2, 2) \ldots$ must satisfy $\mathsf{FTW}(p_{\mathcal{B}}, \lambda)$. However, this sequence does not satisfy $\mathsf{DBTW}(p_{\mathcal{B}})$ nor $\mathsf{DFTW}(p_{\mathcal{B}}, \lambda)$; no even priority smaller than 1 is ever seen, therefore there cannot be any good window at the start of the play.
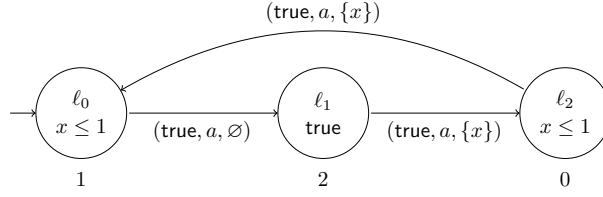
Figure 1 Timed automaton $\mathcal{B}$. Edges are labeled with triples guard-action-resets. Priorities are beneath locations. The incoming arrow with no origin indicates the initial location.

Let us now prove that $\mathsf{DFTW}(p_{\mathcal{B}}, \lambda) \subsetneq \mathsf{DBTW}(p_{\mathcal{B}})$, $\mathsf{FTW}(p_{\mathcal{B}}, \lambda) \subsetneq \mathsf{BTW}(p_{\mathcal{B}})$ and $\mathsf{DBTW}(p_{\mathcal{B}}) \nsubseteq \mathsf{FTW}(p_{\mathcal{B}}, \lambda)$ hold. It suffices to show that $\mathsf{DBTW}(p_{\mathcal{B}}) \setminus \mathsf{FTW}(p_{\mathcal{B}}, \lambda) \neq \emptyset$. We provide a sequence satisfying $\mathsf{DFTW}(p_{\mathcal{B}}, \lambda+1) \subseteq \mathsf{DBTW}(p_{\mathcal{B}})$ but not $\mathsf{FTW}(p_{\mathcal{B}}, \lambda)$. For instance, consider the sequence of states $(\ell_0, 0, 0)(\ell_1, 0, 0)(\ell_2, 0, \lambda)(\ell_0, 0, \lambda)(\ell_1, 0, \lambda)(\ell_2, 0, 2\lambda)\ldots$ obtained by repeatedly using action a with a delay of 0 in ℓ_0, then action a with a delay of λ in ℓ_1 and finally action a in ℓ_2 with a delay of 0. The timed good window objective $\mathsf{TGW}(p, \lambda + 1)$ is satisfied by every suffix of this sequence; there is a delay of λ between an occurrence of the priority 1 and the smaller even priority 0. Therefore, the objective $\mathsf{DBTW}(p_{\mathcal{B}})$ is satisfied. However, the fixed objective $\mathsf{FTW}(p_{\mathcal{B}}, \lambda)$ is not satisfied; any suffix of this sequence starting in location ℓ_0 does not satisfy the timed good window objective $\mathsf{TGW}(p_{\mathcal{B}}, \lambda)$ due to the delay spent in location ℓ_1. The relations $\mathsf{DFTW}(p_{\mathcal{B}}, \lambda) \subsetneq \mathsf{DBTW}(p_{\mathcal{B}})$ and $\mathsf{FTW}(p_{\mathcal{B}}, \lambda) \subsetneq \mathsf{BTW}(p_{\mathcal{B}})$ follow from this example and inclusions of Lemma 3.

It remains to show that $\mathsf{BTW}(p_{\mathcal{B}}) \subsetneq \mathsf{Parity}(p_{\mathcal{B}})$ holds. Initialize n to 0. We consider the sequence of states induced by the path obtained by sequentially using the moves $(0, a)$ in location ℓ_0, (n, a) in location ℓ_1 and $(0, a)$ in location ℓ_2, increasing n and then repeating the procedure. This sequence of states satisfies the parity objective; the smallest priority seen infinitely often is 0. However, it does not satisfy $\mathsf{BTW}(p)$. At each step of the construction of the path, a delay of n takes place between priority 1 in ℓ_0 and priority 0 in ℓ_2. No matter the chosen suffix of the sequence of states and the chosen bound λ, the objective $\mathsf{DFTW}(p_{\mathcal{B}}, \lambda)$ cannot be satisfied, therefore the objective $\mathsf{BTW}(p_{\mathcal{B}})$ is not satisfied. ◄

▶ Remark 5. In the location ℓ_1 of the previous TA, the invariant true allows us to wait for an arbitrary amount of time in ℓ_1. However, this aspect of the TA is not crucial to illustrate that the inclusions of Lemma 3 are strict.

It is possible to obtain an example TA in which the claims of Lemma 4 hold and such that invariants prevent time from diverging without infinitely often traversing edges. This can be accomplished by a straightforward adaptation of the TA $\mathcal{B}$ of Figure 1; it suffices to change the invariant of ℓ_1 to $x \leq 1$ and add an edge from ℓ_1 to itself that resets x. Such an alteration does not change the behavior of the TA.

The proof of Lemma 4 illustrates that window parity objectives, in general, are a strict strengthening of parity objectives. Furthermore, it shows that, in general, there is no uniform bound λ such that all paths satisfying a direct or indirect bounded timed window objective satisfy the corresponding fixed objective for λ. However, we show in Section 4 that if all time-divergent paths of a TA satisfy a (respectively direct) bounded timed window objective, then one can find a bound λ such that all paths satisfy the (respectively direct) fixed timed window objective for λ (Corollaries 8 and 10). Similarly, in TGs, $\mathcal{P}_1$ has a winning strategy for a bounded objective if and only if they have a winning strategy for some corresponding fixed objective (Theorems 17 and 22). In the sequel, we do not consider algorithms based on reductions to the direct case; the bounds used to reduce bounded objectives to fixed

objective may be large and induce an otherwise avoidable computational cost. This justifies alternative approaches.

3.3 Simplifying paths violating window objectives

In this section, we provide a technical result used for the verification and realizability of bounded timed window objectives. First, we introduce some terminology. We say a path $\pi = s_0 \xrightarrow{m_0} s_1 \ldots$ of $\mathcal{A}$ (respectively, a play $\pi = s_0(m_0^{(1)}, m_0^{(2)})s_1 \ldots$ of $\mathcal{G}$) eventually follows the cycle $(\ell_0, R_0) \xrightarrow{\tau} \ldots \xrightarrow{\tau} (\ell_n, R_n)$ of the region abstraction if there exists $i \in \mathbb{N}$ such that for all $j \in \{i, i+1, \ldots, i+n-1\}$ and all $k \in \mathbb{N}$, $[s_{j+n\cdot k}] = (\ell_j, R_j)$. We say that a cycle of the region abstraction is *time-divergent* if all paths of the TA (or, equivalently, all plays of the TG) that eventually follow this cycle are time-divergent.

The main result of this section allows us to extract time-divergent cycles in the region abstraction from a path or play violating a timed good window objective for a sufficiently large bound. This result can then be applied to any path or play that violates the direct or indirect bounded timed window objective; it follows from the definition that, for any bound λ, there is a suffix violating the timed good window objective for λ.

For the sake of generality, we abstract whether we consider paths or plays: we state the upcoming result in terms of sequences of states. In practice, only the actions are abstracted away; delays between states are encoded by the global clock γ. We say that for any sequence of states $s_0 s_1 \ldots \in S^\omega$, the delays are bounded by $B \in \mathbb{N}$ if $v_{n+1}(\gamma) - v_n(\gamma) \leq B$ for all $n \in \mathbb{N}$. We also extend this terminology to paths and plays via their induced sequence of states.

The rough idea of the following lemma is as follows: assuming that delays are bounded along a sequence of states, if the timed good window objective is violated for some large enough bound $\lambda \in \mathbb{N}$, it is possible to find within λ time units from the start of the sequence a time-divergent cycle in the region abstraction.

In the context of TGs, we will seek to apply the result to construct an outcome of a given finite-memory region strategy violating a window objective. A *deterministic finite automaton* (DFA) over state regions is a tuple $(\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}})$ where $\mathfrak{M}$ is a finite set of states, $\mathfrak{m}_{\mathsf{init}} \in \mathfrak{M}$ and $\alpha_{\mathsf{up}} \colon \mathfrak{M} \times (L \times \mathsf{Reg}) \to \mathfrak{M}$. Given a Mealy machine $\mathcal{M} = (\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}}, \alpha_{\mathsf{mov}})$ encoding a finite-memory region strategy, we refer to $(\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}})$ as the DFA underlying $\mathcal{M}$. Showing that we can find cycles in the region abstraction gives us no information on the finite-memory strategy. Therefore, we instead require the stronger claim that we can find a cycle in the product of the region abstraction of $\mathcal{A}$ and the underlying DFA within the first λ time units of the sequence of states.

▶ **Lemma 6.** *Let $(\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}})$ be a DFA. Let $\pi = s_0 s_1 s_2 \ldots \in S^\omega$ be a sequence of states induced by some time-divergent path or play in which delays are bounded by 1, and $\mathfrak{m}_0 \mathfrak{m}_1 \mathfrak{m}_2 \ldots \in \mathfrak{M}^\omega$ be the sequence inductively defined by $\mathfrak{m}_0 = \mathfrak{m}_{\mathsf{init}}$ and $\mathfrak{m}_{k+1} = \alpha_{\mathsf{up}}(\mathfrak{m}_k, [s_k])$. Let $\lambda = 2 \cdot |L| \cdot |\mathsf{Reg}| \cdot |\mathfrak{M}| + 3$. If $\pi \notin \mathsf{TGW}(p, \lambda)$, then there exist some indices $i < j$ such that $([s_i], \mathfrak{m}_i) = ([s_j], \mathfrak{m}_j)$, the global clock γ passes some integer bound between indices i and j, and strictly less than λ time units elapse before reaching s_j from s_0.*

Proof. Assume that $\pi \notin \mathsf{TGW}(p, \lambda)$. For any $j \in \mathbb{N}$, let v_j denote the clock valuation of s_j. Because we assume that π is induced by a path or play, the sequence $(v_j(\gamma))_{j \in \mathbb{N}}$ is non-decreasing. It follows that the set $\{j \in \mathbb{N} \mid v_j(\gamma) - v_0(\gamma) < \lambda\}$ is an interval. Let $j^\star$ denote the greatest element of this interval; $j^\star$ is well-defined because we assume that π is induced by some time-divergent path or play. We let $h = s_0 \ldots s_{j^\star}$ be the prefix of π in

which strictly less than λ time units have elapsed. Observe that because delays between states are at most of 1 and $v_{j^\star+1}(\gamma) - v_0(\gamma) \geq \lambda$, it follows that $v_{j^\star}(\gamma) - v_0(\gamma) \geq \lambda - 1$.

We find the sought indices i and j by progressively checking each index up to $j^\star$ by induction. We mark elements $([s_i], \mathfrak{m}_i) \in (L \times \mathsf{Reg}) \times \mathfrak{M}$ as unsuitable if at step i of our search there is no $j > i$ such that $([s_i], \mathfrak{m}_i) = ([s_j], \mathfrak{m}_j)$ and $\lfloor v_i(\gamma) \rfloor < \lfloor v_j(\gamma) \rfloor$ (i.e., the global clock passes a new integer bound). If at any step we do not mark the current region as unsuitable, we have found the sought indices i and j and stop the search procedure.

In the remainder of this proof, we show that the procedure must terminate by finding a suitable pair of indices. By contradiction, we assume that all elements of $(L \times \mathsf{Reg}) \times \mathfrak{M}$ appearing in $([s_0], \mathfrak{m}_0) \ldots ([s_{j^\star}], \mathfrak{m}_{j^\star})$ are marked as unsuitable, i.e., the search of a suitable pair fails.

Any $([s], \mathfrak{m}) \in (L \times \mathsf{Reg}) \times \mathfrak{M}$ that is marked as unsuitable during the search procedure can only appear again at most one time unit after its first appearance, otherwise it would not have been marked as unsuitable. This implies that whenever a pair $([s], \mathfrak{m})$ is marked as unsuitable, there is some point fixed in time from its first appearance after which it no longer appears in h, i.e., there is some $\delta \in \mathbb{R}_{\geq 0}$ (depending on the smallest index for which we witness the pair) such that for all $i \leq j^\star$, $v_i(\gamma) \geq v_0(\gamma) + \delta$ implies $([s_i], \mathfrak{m}_i) \neq ([s], \mathfrak{m})$, in which case we say that the pair $([s], \mathfrak{m})$ is eliminated by (as shorthand for can no longer appear from) time δ. We give lower bounds on the number of eliminated pairs depending on the time that has passed. We reach a contradiction by showing that we run out of pairs in $(L \times \mathsf{Reg}) \times \mathfrak{M}$ before we reach $j^\star$.

We claim that at least n pairs are eliminated by time $2n - 1$. We prove this by induction. The base case is handled by considering the first elements of the sequence: $(s_0, \mathfrak{m}_0)$ is eliminated by time 1. Let $k_1 \leq j^\star$ denote the latest index such that $([s_0], \mathfrak{m}_0) = ([s_{k_1}], \mathfrak{m}_{k_1})$. This index occurs at most one time unit after index 0.

Now assume inductively that we have shown that (at least) n distinct pairs $([s_{k_1}], \mathfrak{m}_{k_1})$, $\ldots$, $([s_{k_n}], \mathfrak{m}_{k_n})$ (where $k_i \leq j^\star$ denotes the index of the last occurrence of a pair) are eliminated by time $2n - 1$. It follows that $([s_{k_n+1}], \mathfrak{m}_{k_n+1})$ is eliminated at most 2 time units after the elimination of $([s_{k_n+1}], \mathfrak{m}_{k_n+1})$: there is at most 1 time unit between indices k_n and $k_n + 1$, and at most 1 time unit between the first and last occurrence of $([s_{k_n+1}], \mathfrak{m}_{k_n+1})$. This shows that there are $n + 1$ eliminated pairs by time $2n + 1$.

It follows that all elements of $(L \times \mathsf{Reg}) \times \mathfrak{M}$ are eliminated at time $\lambda - 2$, i.e., there are no more pairs that can appear in h after this time. However, we have $v_{j^\star}(\gamma) - v_0(\gamma) \geq \lambda - 1$, i.e., it is absurd to have had $([s_{j^\star}], \mathfrak{m}_{j^\star})$ eliminated.   ◀

The main interest of the lemma is to construct witness paths or plays that violate the direct bounded timed window objective. By following the sequence of states up to index i and then looping in the cycle formed by the sequence of states from i to index j (modulo clock-equivalence), one obtains a path along which, at all steps, the smallest priority seen from the start is odd, i.e., such that no good window can ever be witnessed from the start.

4   Verification of timed automata

In this section, we are concerned with the verification of direct and indirect bounded timed window objectives in TAs. For both objectives, we show the equivalence of the following assertions: (1) there exists a time-divergent witness to the violation of a (direct) bounded objective, (2) there exists a time-divergent witness to the violation of the matching (direct) fixed objective for a sufficiently large bound, and (3) there exists a set of states (regions) reachable from one another verifying some properties that we describe later in this section.

Nondeterministic algorithms for the verification of the objectives are obtained by guessing appropriate regions and checking that they are reachable from one another.

The outline of the section is as follows. Section 4.1 describes criteria attesting to the existence of time-divergent paths violating the direct and indirect bounded timed window objectives in timed automata. Verification algorithms are described in Section 4.2.

We fix for this entire section a TA $\mathcal{A} = (L, \ell_{\mathsf{init}}, C, \Sigma, I, E)$ and a priority function $p\colon L \to \{0, \ldots, \mathsf{D} - 1\}$.

4.1 Equivalent conditions to the violation of bounded objectives

In this section, we provide conditions equivalent to the existence of paths violating the direct and indirect bounded timed window objectives. We are also concerned with the question of uniformity of time bounds; we show that in a timed automaton in which all time-divergent paths satisfy a direct or indirect bounded timed window objective, there exists a bound for which a direct or indirect fixed objective is satisfied.

4.1.1 Direct bounded timed window objectives

A path satisfies the direct bounded timed window objective if at all steps, there is a good window and the size of these good windows is bounded overall. Therefore, a path can violate this objective in one of two ways. First, it may be the case that at some step, no good window of any size is witnessed. Second, it may be the case that good windows are witnessed at all steps, but that there is no bound on the size of these windows.

We show that whenever some time-divergent path violates the direct bounded timed window objective, there is always some witness that falls in the first category. Furthermore, a witness that takes the form of a path that eventually follows a time-divergent cycle of the region abstraction can be chosen.

Given a time-divergent path π violating the direct bounded timed window objective, the rough idea to derive a suitable witness is the following. We consider some state s_1 along π from which there is no good window for the window size λ in the statement of Lemma 6 (assuming that the DFA has only one state). We obtain through this lemma two region-equivalent states s_2 and s_2' appearing in π within λ time units of s_1, such that in the path fragment of π between s_2 and s_2', the global clock γ passes a new integer value. As explained in Section 3.3, we can construct a path violating the direct bounded window objective by following π up to s_2 and then following a path that repeats the time-divergent cycle in the region abstraction induced by the sequence of states between s_2 and s_2' in π.

The states described in the construction above can be characterized as follows. First, there must be a finite path from the state s_1 to the state s_2 in which the smallest priority in all prefixes is odd. Second, we require that $[s_2]$ be reachable from s_2 without witnessing a good window from s_1 and also in such a way that the global clock γ passes a new integer bound. The latter property can also be translated to reachability requirements; we require that, on the sought path from s_2 to its state region, there be states s_3 and s_4 such that the valuation of γ is integral in only one of the two states s_3 and s_4.

We show hereunder that the existence of a time-divergent path violating the direct bounded timed window objective is equivalent to the existence of states satisfying the properties above. Because we need only consider a state from which there is no good window for the bound λ of Lemma 6, these two conditions are also equivalent to the existence of a time-divergent path violating $\mathsf{DFTW}(p, \lambda)$.

▶ **Theorem 7.** *The following three statements are equivalent.*

1. *There exists a time-divergent initial path $\pi \notin \mathsf{DBTW}(p)$.*
2. *There exists a time-divergent initial path $\pi \notin \mathsf{DFTW}(p, 2 \cdot |L| \cdot |\mathsf{Reg}| + 3)$.*
3. *There exist reachable states s_1, s_2, s_2', s_3 and s_4 such that $s_2 \equiv_{\mathcal{A}} s_2'$, the valuation of γ is integral in only one of the two states s_3 and s_4, and there is a finite path h from s_1 to s_2' passing through s_2, s_3 and s_4 in order such that the smallest priority in all of the prefixes of h is odd.*

Proof. Let $\lambda = 2 \cdot |L| \cdot |\mathsf{Reg}| + 3$. This λ is the bound of Lemma 6 assuming a deterministic finite automaton with a single state. The implication ($1 \implies 2$) follows directly from the inclusion $\mathsf{DFTW}(p, \lambda) \subseteq \mathsf{DBTW}(p)$.

We move on to the proof of ($2 \implies 3$). Let us assume there is some time-divergent initial path $\pi \notin \mathsf{DFTW}(p, \lambda)$. We may assume without loss of generality that delays in π are bounded by 1: moves (δ, a) with large delays can be simulated by using $\lfloor \delta \rfloor$ moves of the form $(1, \bot)$ followed by the move $(\mathsf{frac}(\delta), a)$. It can easily be shown that the objective is still violated following this modification.

Let s_1 be some state of π such that some suffix π' of π starting in s_1 violates the timed good window objective $\mathsf{TGW}(p, \lambda)$. It follows from Lemma 6 that there are two region-equivalent states s_2 and s_2' in π' within the first λ time units such that, in π', the global clock passes an integer bound between the two states.

One can take $s_3 = s_2$. If in s_2, the valuation of γ is an integer (resp. not an integer), take s_4 to be any state in the path from s_2 to s_2' in π' that has a non-integral (resp. integral) valuation. If no such state exists, it suffices to split a move (δ, a) in π' into two well-chosen moves $(\delta_1, \bot)$ and (δ_2, a) where $\delta = \delta_1 + \delta_2$ and the global clock γ is not equal to an integer (respectively is equal to an integer) after δ_1 time units elapse. It follows from $\pi' \notin \mathsf{TGW}(p, \lambda)$ that s_1, s_2, s_2', s_3 and s_4 satisfy the requirement of the theorem. This ends this direction of the proof.

Finally, let us establish the implication ($3 \implies 1$). Assume now that we have the states s_1, s_2, s_2', s_3, s_4 and h satisfying the properties in the statement of the theorem. Let h' denote the suffix of h between states s_2 and s_2'. We argue that any initial path π obtained by reaching s_1 from s_{init} (by any means), then following h up to s_2, and then following the cycle in the region abstraction induced by h' is time-divergent and violates $\mathsf{DBTW}(p)$. Fix one such path π and let π' denote its suffix starting from s_1.

First, let us argue the time-divergence of π. The path π passes through states that are equivalent to s_3 and to s_4 infinitely often. In other words, the global clock γ is infinitely often an integer, and infinitely often not an integer. It follows from the fact that γ cannot be reset that it must pass infinitely many integer bounds, i.e., π is time-divergent.

Second, let us move on to showing that $\pi \notin \mathsf{DBTW}(p)$. It suffices to show that no matter the bound $\lambda \in \mathbb{N}$, the objective $\mathsf{TGW}(p, \lambda)$ is violated by π'. This can be established by showing that in any prefix of π', the smallest priority that occurs is odd. For any prefix of π' that is a prefix of h, this property follows from our hypothesis on h. For any subsequent prefix, no new priorities are introduced as we repeat a cycle in the region abstraction following the suffix h' of h. This shows that $\pi \notin \mathsf{DBTW}(p)$ and ends the proof of this implication.

◀

In light of Theorem 7, we directly obtain the following corollary.

▶ **Corollary 8.** *Let $\lambda = 2 \cdot |L| \cdot |\mathsf{Reg}| + 3$. All time-divergent paths of $\mathcal{A}$ satisfy $\mathsf{DBTW}(p)$ if and only if all time-divergent paths of $\mathcal{A}$ satisfy $\mathsf{DFTW}(p, \lambda)$.*

Even though the corollary above suggests that we can reduce verification of bounded objectives to verification of fixed objectives, the verification of fixed objectives requires time

polynomial in the supplied time bound. Intuitively, one must explore the region abstraction of a TA derived from $\mathcal{A}$ in which an additional clock $z \notin C$ is introduced and increases up to the bound of the objective. Given that the bound provided by Lemma 6 is large, we develop approaches that avoid the cost incurred by this reduction.

4.1.2 Bounded timed window objective

We now move on to the bounded timed window objective. In this case, time-divergent paths that eventually repeat a cycle of the region abstraction no longer suffice as witnesses to the violation of the objective. In the direct case, the finite path preceding the cycle mattered in the violation, e.g., if an odd priority smaller than all those of the cycle appeared along this path. However, in such paths, only the cycle itself would matter by prefix-independence for the indirect objective.

Lemma 4 asserts the existence of a TA in which all time-divergent paths satisfy the parity objective, but some violate the bounded timed window objective. This implies that even if all time-divergent cycles in the region abstraction have an even smallest priority, this does not ensure the satisfaction of the bounded timed window objective. It follows that the form of witnesses is more complex in this case.

Nonetheless, witnesses can be always be found with a recursive structure. Assume that some time-divergent path violates the bounded timed window objective. Then there is a another violating path operating in stages labeled by natural numbers $n \in \mathbb{N}$, with each stage divided in two parts. In the first part of stage n, we visit some well-chosen fixed state region $[s]$ from which there is a time-divergent path that violates the direct bounded objective. Once a state belonging to such a region is reached, we can follow a time-divergent path violating the direct objective that eventually follows a cycle in the region abstraction for (at least) n time units, before moving on to stage $n + 1$.

In the direct case, Theorem 7 essentially states that one can find a witness to the violation of the objective if and only if there exists reachable states s_1, s_2 and s_2' such that $s_2 \equiv_{\mathcal{A}} s_2'$, there is a finite path h from s_1 to s_2' passing through s_2 such that the smallest priority in any prefix of h is odd and an integer bound is passed by the global clock between s_2 and s_2' in h. The characterization in the prefix-independent case is only slightly stronger: we only require, in addition to the above, that $[s_1]$ be reachable from s_2, without any constraints on the path between these two states. Intuitively, we return to $[s_1]$ whenever a stage has ended. One such state is easy to find: there are finitely many regions and infinitely many suffixes of the path from which there are no good windows for some sufficiently large bound, therefore some region must repeat.

We formalize our characterization below. Similarly to the direct case, one can also show that the existence of a time divergent path violating $\mathsf{BTW}(p)$ is equivalent to the existence of a time-divergent path violating $\mathsf{FTW}(p, \lambda)$ for the bound λ of Lemma 6.

▶ **Theorem 9.** *The following three statements are equivalent.*
1. *There exists a time-divergent initial path $\pi \notin \mathsf{BTW}(p)$.*
2. *There exists a time-divergent initial path $\pi \notin \mathsf{FTW}(p, 2 \cdot |L| \cdot |\mathsf{Reg}| + 3)$.*
3. *There exist reachable states s_1, s_2, s_2', s_3 and s_4 such that $s_2 \equiv_{\mathcal{A}} s_2'$, the valuation of γ is integral in only of the two states s_3 and s_4, there is a finite path h from s_1 to s_2' passing through s_2, s_3 and s_4 (in order) such that the smallest priority in all of the prefixes of h is odd, and the region $[s_1]$ is reachable from s_2'.*

Proof. Let $\lambda = 2 \cdot |L| \cdot |\mathsf{Reg}| + 3$ be the bound of Lemma 6 assuming a deterministic finite automaton with a single state. The implication ($1 \implies 2$) follows directly from the inclusion

$\mathsf{FTW}(p, \lambda) \subseteq \mathsf{BTW}(p)$.

To establish the implication ($2 \implies 3$), we explain how to adapt the proof of Theorem 7 to derive the five states from a time-divergent initial path $\pi \notin \mathsf{FTW}(p, \lambda)$. Let us assume that there is some time-divergent initial path $\pi \notin \mathsf{FTW}(p, \lambda)$. In particular, $\pi \notin \mathsf{DFTW}(p, \lambda)$. It is shown in the proof of Theorem 7 that by taking any state s_1 in π such that some suffix π' of π starting in s_1 violates the timed good window objective $\mathsf{TGW}(p, \lambda)$, we can find the sought-after states s_2, s_2', s_3 and s_4, without the requirement that $[s_1]$ be reachable from s_2'.

To ensure that $[s_1]$ is reachable from a matching s_2', we choose a state s_1 subject to some constraints. We show that there must be some state s_1 in π such that some suffix π' starting in s_1 satisfies $\pi' \notin \mathsf{TGW}(p, \lambda)$ and such that there are states equivalent to s_1 infinitely often in π'. Because the region $[s_1]$ occurs infinitely often along π, there is an occurrence after the appearance of s_2'. This makes one such s_1 a good choice. The proof of existence of one such s_1 follows.

Let $I = \{i \in \mathbb{N} \mid \pi_{i \to} \notin \mathsf{TGW}(p, \lambda)\}$. The set I must be infinite, otherwise there would be some $j \in \mathbb{N}$ such that for all $i \geq j$, $\pi_{i \to} \in \mathsf{TGW}(p, \lambda)$, i.e., $\pi_{j \to} \in \mathsf{DFTW}(p, \lambda)$, which would imply $\pi \in \mathsf{FTW}(p, \lambda)$. Because I is infinite and there are finitely many state regions, one can find a state s_1 in π indexed by an element in I such that its state region is visited infinitely often along π. This ends the proof of this implication.

Let us now move on to the implication ($3 \implies 1$). Assume the existence of states s_1, s_2, s_2', s_3 and s_4 subject to the constraints above. We construct a time-divergent initial path $\pi \notin \mathsf{BTW}(p)$ inductively. We denote by π_n the path constructed at step n of the induction. We let π_0 be any finite path to s_1 from s_{init}. Let us now assume that we are at induction step $n \geq 1$, and by induction that the last state of π_{n-1} is in $[s_1]$. We split the counterpart in the region abstraction of the path from s_1 through s_2, s_3, s_4 to s_2' given by our hypothesis into two parts: h_{Reg} for the part up to $[s_2]$ (not included) and h_{Reg}' for the remaining cycle from $[s_2]$ to itself. We extend π_{n-1} by appending to it some path in $\mathcal{A}$ following the path $h_{\mathsf{Reg}}(h_{\mathsf{Reg}}')^{n+1}$ in the region abstraction, and then any path from $[s_2]$ back to $[s_1]$, so that we can continue the inductive construction.

The path π obtained through the inductive construction above is time-divergent; the global clock, which cannot be reset, alternates between taking an integer value and not taking an integer value infinitely often, therefore its valuation must diverge. We now argue that π violates $\mathsf{BTW}(p)$, i.e., we argue that for all suffixes of π, for all $\lambda \in \mathbb{N}$, $\mathsf{DFTW}(p, \lambda)$ is not satisfied by the suffix. By construction, the path appended at step n of the construction aside from the return to $[s_1]$ is such that, in all of its prefixes, the smallest priority is odd. Furthermore, the duration of this path is of at least n time units: we witness the global clock pass an integer bound at least $n + 1$ times in this path. It follows that the suffix of π after π_{n-1} violates $\mathsf{TGW}(p, n)$. Because we let n grow to infinity in the construction, no suffix of π satisfies a direct fixed timed window objective. This ends the proof. ◀

In light of Theorem 9, we directly obtain the following corollary.

▶ **Corollary 10.** *Let $\lambda = 2 \cdot |L| \cdot |\mathsf{Reg}| + 3$. All time-divergent paths of $\mathcal{A}$ satisfy $\mathsf{BTW}(p)$ if and only if all time-divergent paths of $\mathcal{A}$ satisfy $\mathsf{FTW}(p, \lambda)$.*

4.2 Verification algorithms

In this section, we discuss verification algorithms for the direct and indirect bounded objectives. In Section 4.2.1, we provide a useful procedure to check, given some states of the TA, the existence of paths subject to the constraints of Theorems 7 and 9. We then discuss non-deterministic verification algorithms and their complexity in Section 4.2.2.

4.2.1 Checking reachability with priority-induced constraints

In the two previous sections, we have identified conditions for the existence of paths violating the direct bounded timed window objectives and the bounded timed window objectives. These criteria involve the existence of states such that one can find a path traversing these states where, in any prefix of this path, the smallest priority that occurs is odd, i.e., we construct paths along which no good window is identified. We argue in the sequel that the existence of such paths can be decided in polynomial space. We will outline a non-deterministic polynomial space procedure; the previous claim follows from the equality PSPACE = NPSPACE [36].

This complexity can be justified by a straightforward adaptation of the classical algorithm for reachability in timed automata [2]. The idea is to detect a suitable path by means of the region abstraction. The region abstraction itself is exponential in the size of the TA, but needs not be constructed entirely to check whether some region is reachable. An NPSPACE algorithm for reachability can operate by exploring the region abstraction on-the-fly, and keeping track of a region and the current number of steps taken in the current path. The algorithm returns a positive answer if a target is reached, and a negative answer if the step counter reaches the size of the region abstraction. Because regions are representable in polynomial space and the counter can be represented in binary, the claimed complexity follows.

In the sequel, we require a slight variant of this algorithm. We are given a certain number of regions $[s_1], \ldots, [s_n]$ and want to determine whether one path exists traversing these regions in such a way that the smallest priority witnessed from the start of the path is odd at all times. The classical algorithm can be extended naturally to handle multiple sequential targets and the priority-related constraints.

To handle the visiting of multiple regions in order, it suffices, each time a target is reached, to reset the step counter and update the target to the next one. One returns a positive answer if all targets have been reached. This induces an increase in memory at most linear in the number of targets: one can simply keep track of the current target by means of its index in the sequence of targets. In practice, we use this procedure with five targets.

For the priority-related constraints, it suffices to keep track of the smallest priority witnessed from the start of the guessed path (unlike the counter above, this priority should never be reset). We add an additional condition: the decision procedure stops and returns a negative answer if this priority becomes even at any point. This induces an increase in memory of at most $\log_2(d)$ bits. Overall, this modified procedure still only uses polynomial space. We therefore obtain the following lemma.

▶ **Lemma 11.** *The existence of a path passing through n given regions in order such that the smallest priority of all of its prefixes is odd is decidable in deterministic polynomial space.*

4.2.2 Algorithms for the verification of bounded timed window objectives

We can now describe the complexity of the verification problem for direct and indirect bounded timed window objectives. We first describe algorithms for the dual problem of verification, i.e., algorithms that check whether there exists a time-divergent path that violates the considered objective. These algorithms use oracles to check reachability properties between regions. The complexity of our algorithms is in $\mathsf{NP}^{\mathsf{PSPACE}} = \mathsf{PSPACE}$ [6]. The idea is to guess five state regions and then check whether they conform to the conditions in Theorems 7 and 9.

We use two oracles in PSPACE. The first oracle returns, given two regions, whether there is a path in the region abstraction from the first region to the second, i.e., this oracle decides standard reachability. The second oracle encodes the problem formulated in Lemma 11.

To decide the existence of a time-divergent path violating the direct objective, we guess five regions and check if they satisfy the conditions of Theorem 7. This algorithm consists of guessing the regions, checking whether the first region is reachable from the initial state using the first oracle and then using the second oracle to confirm the satisfaction of conditions of Theorem 7. For the indirect objective, we proceed similarly to check the conditions of Theorem 9; the only difference to the direct case is that there is an additional call to the first oracle. This shows that the dual problem of verification for direct and indirect bounded timed window objectives is in $\mathsf{NP}^{\mathsf{PSPACE}} = \mathsf{PSPACE}$. Because PSPACE is closed under complementation, the PSPACE-membership of the verification problem for direct and indirect bounded timed window objectives follows.

▶ **Lemma 12.** *The verification problems for direct and indirect bounded timed window objectives are in* PSPACE.

Let us now assume that the priority function $p\colon L \to \{0, \ldots, \mathsf{D}-1\}^{\mathsf{K}}$ is multi-dimensional. Verifying that all time-divergent paths satisfy a generalized objective is equivalent to checking that a one-dimensional objective is verified on each dimension. It follows from Lemma 12 and $\mathsf{P}^{\mathsf{PSPACE}} = \mathsf{PSPACE}$ [6] that the verification of multi-dimensional objectives can be done in polynomial space.

▶ **Theorem 13.** *The verification problems for generalized direct and indirect bounded timed window are in* PSPACE.

5   Solving timed games

In this section, we propose an algorithmic solution to the realizability problem for direct and indirect bounded timed window parity objectives. For the direct case, we provide a reduction to the realizability problem for an ω-regular region objective in Section 5.1: we show that to enforce the direct bounded objective, we can consider the objective requiring that any odd priority is followed by a smaller even priority. In Section 5.2, we provide a fixed-point algorithm for the indirect case, which intuitively iterates the computation of a winning set for the direct case.

For this entire section, we fix a TG $\mathcal{G} = (\mathcal{A}, \Sigma_1, \Sigma_2)$ with $\mathcal{A} = (L, \ell_{\mathsf{init}}, C, \Sigma_1 \cup \Sigma_2, I, E)$ and a multi-dimensional priority function $p\colon L \to \{0, \ldots, \mathsf{D}-1\}^{\mathsf{K}}$.

5.1   Direct bounded timed window objective

In this section, we provide a reduction from the realizability problem for the generalized direct bounded timed window objective to the realizability problem for the untimed ω-regular request-response objective [37, 19]. In Section 5.1.1, we introduce the request-response objective and explain how to derive a request-response objective from the multi-dimensional priority function p. In Section 5.1.2, we show that the set of winning states for this request-response objective coincides with the winning set for the generalized direct bounded timed window objective and that this set coincides even with the winning set of some generalized direct fixed timed window objective.

5.1.1   Request response-objectives

A request-response objective is an ω-regular region objective defined by a family of pairs of sets of state regions $\mathcal{R} = ((\mathsf{Rq}_j, \mathsf{Rp}_j))_{j=1}^r$. The request-response objective for $\mathcal{R}$ requires that for all $k \in \{1, \ldots, r\}$, for any visit to a state region in Rq_k, there must be a location in Rp_k appearing later in the play. We refer to state regions in Rq_k as requests and to state regions in Rp_k as responses.

Let $\mathcal{R} = ((\mathsf{Rq}_k, \mathsf{Rp}_k))_{k=1}^r$ be a family of request-response pairs. Formally, we define the request-response objective $\mathsf{RR}(\mathcal{R})$ as the set of sequences of states

$$\{s_0 s_1 \ldots \in S^\omega \mid \forall\, k \leq r,\ \forall n,\ \exists n' \geq n,\ [s_n] \in \mathsf{Rq}_k \implies [s_{n'}] \in \mathsf{Rp}_k\}.$$

A DPA in which the only priorities are 0 and 1 are equivalent to the deterministic Büchi automata (DBAs) of the literature. In general, for a request-response objective with r request-response pairs, a DBA with $2^r \cdot r$ states suffices [37]. The request-response families we define later from priority functions have $\lfloor \frac{\mathsf{D}}{2} \rfloor \cdot \mathsf{K}$ request-response pairs. Hence, using such a DBA in our game solving approach induces an exponential blow-up in the number of priorities in the time complexity. We can do better: the request-response objectives we derive from multi-dimensional priority functions can be represented by DBAs with $(\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^{\mathsf{K}} \cdot \mathsf{K}$ states. For a fixed number of dimensions, we obtain a DBA with a number of states polynomial in the number of priorities.

We do not directly introduce small DBAs for the specific request-response families derived from multi-dimensional priority functions. Instead, we define a class of request-response families that subsumes them. We proceed this way due to the indirect case; in the indirect case, we repeatedly solve request-response games in which we alter the sets of requests and responses; by introducing a broader class of request-response families, we achieve a better complexity for these computations with respect to the number of priorities.

We say that a family of request-response pairs $\mathcal{R} = \{(\mathsf{Rq}_1, \mathsf{Rp}_1), \ldots, (\mathsf{Rq}_r, \mathsf{Rp}_r)\}$ is a *chain-response family* if the sets of responses form a chain, i.e., $\mathsf{Rp}_1 \supseteq \mathsf{Rp}_2 \supseteq \ldots \supseteq \mathsf{Rp}_r$ and each set of requests and responses are pairwise disjoint, i.e., for all $i, j \leq r$, $\mathsf{Rq}_i \cap \mathsf{Rp}_j = \emptyset$. In a request-response objective induced by a chain-response family, one needs only keep track of the pending request with the fewest responses, because any response to this request also addresses requests with more responses due to the chain of inclusions. This allows us to define a DBA with $r + 1$ states; there is one state to indicate that no requests are pending, and one state per request to keep track of whichever pending request has fewest responses.

Let $\mathcal{R} = ((\mathsf{Rq}_k, \mathsf{Rp}_k))_{k=1}^r$ be a chain-response family where $\mathsf{Rp}_1 \supseteq \mathsf{Rp}_2 \supseteq \ldots \supseteq \mathsf{Rp}_r$. The request-response objective $\mathsf{RR}(\mathcal{R})$ can be encoded by a DBA $H = (Q, q_{\mathsf{init}}, L \times \mathsf{Reg}, \mathsf{up}, p_H)$ where $Q = \{0, 1, \ldots, r\}$, $q_{\mathsf{init}} = 0$, and up is defined, for all $q \in Q$ and $[s] \in L \times \mathsf{Reg}$,

$$\mathsf{up}(q, [s]) = \begin{cases} 0 & \text{if } q \neq 0 \text{ and } [s] \in \mathsf{Rp}_q \\ \max(\{q\} \cup \{i \leq r \mid [s] \in \mathsf{Rq}_i\}) & \text{otherwise,} \end{cases}$$

and the priority function p_H assigns 0 to state 0 of H and 1 to all other states of H. The DBA H encodes $\mathsf{RR}(\mathcal{R})$. Indeed, H keeps track of the highest seen index of a request and a higher index means fewer responses. Because request and response sets are pairwise disjoint, witnessing the state 0 of H infinitely often is equivalent to having all requests eventually answered.

We say a family of request-response pairs is an *n-chain-response* family if it is a union of n chain-response families. Observe that for all $\mathcal{R}_1, \ldots, \mathcal{R}_n$, we have $\mathsf{RR}(\bigcup_{1 \leq i \leq n} \mathcal{R}_i) = \bigcap_{1 \leq i \leq n} \mathsf{RR}(\mathcal{R}_i)$. The intersection of the languages of n DBAs with $r+1$ states can be encoded

by a DBA with $(r + 1)^n \cdot n$ states [33, Proposition 6.1]. It follows that request-response objectives obtained from n-chain-response families where each underlying chain-response family has at most r pairs can be encoded by DBAs with at most $(r + 1)^n \cdot n$ states.

The following result follows immediately from Theorem 1 and Theorem 2.

▶ **Lemma 14.** *Let $\mathcal{R}$ be an n-chain-response family in which each underlying chain-response family has at most r pairs. The set of winning states in $\mathcal{G}$ for the request-response objective $\mathsf{RR}(\mathcal{R})$ is a union of state regions and can be computed in time $\mathcal{O}((|L| \cdot |\mathsf{Reg}| \cdot (r + 1)^n \cdot n)^3)$, and finite-memory region strategies proposing delays of at most 1 with $4 \cdot (r + 1)^n \cdot n$ states suffice for winning.*

We now explain how we derive a K-chain-response family from a K-dimensional priority function. The idea is to model each odd priority on each dimension as a request, the responses to which are smaller even priorities on the same dimension. A similar construction is used for direct bounded objectives in games in graphs [14].

Assume p is a one-dimensional priority function. We define the chain-response family $\mathcal{R}(p)$ as the family of request-response pairs that contains for each odd priority $j \in \{0, 1, \dots, \mathsf{D}-1\}$, the pair $(\mathsf{Rq}_j, \mathsf{Rp}_j)$ where $\mathsf{Rq}_j = p^{-1}(j) \times \mathsf{Reg}$ and $\mathsf{Rp}_j = \{\ell \in L \mid p(\ell) \leq j \wedge p(\ell) \bmod 2 = 0\} \times \mathsf{Reg}$. This is indeed a chain-response family because the responses to an odd priority are smaller even priorities, and are therefore also responses to any greater odd priorities. If p is K-dimensional, we let $\mathcal{R}(p)$ be the K-chain-response family $\mathcal{R}(p) = \bigcup_{1 \leq i \leq \mathsf{K}} \mathcal{R}(p_i)$.

We close this section by highlighting a nuance between the notion of good windows and the modeling of priorities as requests and responses provided in the definition of $\mathcal{R}(p)$. We consider the one-dimensional case for the upcoming explanation.

Given a state occurring in a play, recall that one finds a good window (of some size about which we are not concerned) if there is a later state on the play such that the smallest priority seen between the two states is even. The earliest response to a request in $\mathcal{R}(p)$ may not induce a good window; it may be the case that on the segment between the request and response, we witness another odd priority for which the first response is not suitable. This new priority must be strictly smaller than that of the initial request; any response to this new request is also strictly smaller than the first response. Assuming that this second request is answered, there may yet again be a strictly smaller odd priority between the second request and response for which the second response is not suitable. We can repeat this reasoning assuming the third request is answered, and so on. However, this phenomenon can only occur finitely often due to the finite number of priorities. The last response in the sequence of responses obtained above is an even priority smaller than any prior odd priority, i.e., we witness a good window eventually assuming that all requests are answered.

It follows that the request-response objective is satisfied if and only if there are good windows from all states along the play. The remaining question addressed in the following section is whether winning for the request-response objective ensures the existence of a winning strategy for which the size of these windows is bounded.

5.1.2 Reducing direct objectives to request-response

The goal of this section is to show that to solve the TG $\mathcal{G}$ with the objective $\mathsf{GDBTW}(p)$, one can solve the TG $\mathcal{G}$ with the request-response objective $\mathsf{RR}(\mathcal{R}(p))$. The main argument consists in showing that the time-divergent outcomes of any winning finite-memory region strategy for the objective $\mathsf{RR}(\mathcal{R}(p))$ proposing bounded delays (the existence of which is ensured by Lemma 14 if $\mathcal{P}_1$ wins) must satisfy $\mathsf{GDFTW}(p, \lambda)$ for some $\lambda \in \mathbb{N}$. This implies that all time-divergent outcomes of one such strategy satisfy $\mathsf{GDBTW}(p)$.

This result is shown by contradiction. We assume that there exists some time-divergent outcome π of one such finite-memory strategy violating $\mathsf{DFTW}(p_k, \lambda)$ on some dimension k for some sufficiently large bound λ; this is ensured whenever one assumes the existence of a time-divergent outcome of σ violating $\mathsf{DBTW}(p_k)$. If this is the case, we can construct an outcome of σ along which, on dimension k, some odd priority is never followed by a smaller even priority, i.e., some request goes unanswered, which contradicts the fact that σ is winning for $\mathsf{RR}(\mathcal{R}(p))$.

The main points of the proof are as follows. There is some suffix π' of π violating the timed good window objective for λ. Within the λ first time units of π', using Lemma 6, one can find two indices such that the TG finds itself in state-equivalent states s and s' and the Mealy machine encoding the winning strategy σ finds itself in the same memory states. Because we consider a finite-memory region strategy, it is possible to inductively construct an outcome of σ which first follows π up to s and then follows the time-divergent cycle in the region abstraction induced by π between s and s'. However, because the smallest priority appearing in all prefixes of π' up to s' is odd (the timed good window objective is violated), it follows that this specific priority is never followed by any smaller even priority, contradicting the fact that σ was winning for $\mathsf{RR}(\mathcal{R}(p))$.

We provide the details hereunder. We prove a slightly stronger statement for later use. Let U be a set of state regions. We show that the announced result holds even if we modify the request-response pairs of $\mathcal{R}(p)$ by removing regions in U from all request sets and adding regions in U to all response sets; that is, any time-divergent outcome of a finite-memory region winning strategy for the modified request-response objective proposing bounded delays satisfies some generalized direct fixed timed window objective, and therefore the generalized direct bounded timed window objective, under the assumption that the regions in U are not visited.

▶ **Lemma 15.** *Let $\mathcal{R}(p) = (\mathsf{Rq}_i, \mathsf{Rp}_i)_{i=1}^r$ be the family of request-response pairs derived from p and $\mathcal{R}' = (\mathsf{Rq}_i \setminus U, \mathsf{Rp}_i \cup U)_{i=1}^r$ for some set of state regions $U \subseteq L \times \mathsf{Reg}$. Let W denote the set of winning states for the objective $\mathsf{RR}(\mathcal{R}')$ and $\mathcal{M} = (\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}}, \alpha_{\mathsf{mov}})$ be a Mealy machine encoding a finite-memory region winning strategy of $\mathcal{P}_1$ from W for the objective $\mathsf{RR}(\mathcal{R}')$ proposing delays of at most 1. Let $\pi = s_0(m_0^{(1)}, m_0^{(2)})s_1 \ldots$ be a time-divergent outcome of the strategy induced by $\mathfrak{M}$ such that $s_0 \in W$ and let $\lambda = 2 \cdot |L| \cdot |\mathsf{Reg}| \cdot |\mathfrak{M}| + 3$. If for all $n \in \mathbb{N}$, $[s_n] \notin U$ then $\pi \in \mathsf{GDFTW}(p, \lambda) \subseteq \mathsf{GDBTW}(p)$.*

Proof. Assume that $\pi \notin \mathsf{GDFTW}(p, \lambda)$ by contradiction. We fix a dimension $k \in \{1, \ldots, \mathsf{K}\}$ such that $\pi \notin \mathsf{DFTW}(p_k, \lambda)$. Let σ denote the strategy induced by $\mathcal{M}$. We consider the sequence $\mathfrak{m}_0\mathfrak{m}_1 \ldots \in \mathfrak{M}^\omega$ of memory states witnessed along π, given by $\mathfrak{m}_0 = \mathfrak{m}_{\mathsf{init}}$ and for all $n \in \mathbb{N}$, $\mathfrak{m}_{n+1} = \alpha_{\mathsf{up}}(\mathfrak{m}_n, [s_n])$.

Recall that λ is the bound of Lemma 6 using the DFA underlying $\mathcal{M}$. It follows from our assumption of $\pi \notin \mathsf{DFTW}(p_k, \lambda)$ that there is some $n_0 \in \mathbb{N}$ such that $\pi_{n_0 \to} \notin \mathsf{TGW}(p_k, \lambda)$. By Lemma 6, there exists two indices $n_1, n_2 \geq n_0$ such that $n_1 < n_2$, $s_{n_1} \equiv_\mathcal{A} s_{n_2}$, $\mathfrak{m}_{n_1} = \mathfrak{m}_{n_2}$ and $\lfloor v_{n_1}(\gamma) \rfloor < \lfloor v_{n_2}(\gamma) \rfloor$, and for all $n_0 \leq n' \leq n_2$, we have $\min_{n_0 \leq n \leq n'} p(\ell_n)$ is odd, where $s_n = (\ell_n, v_n)$ for all $n \in \mathbb{N}$.

We now construct a time-divergent outcome $\widetilde{\pi} = \widetilde{s}_0(\widetilde{m}_0^{(1)}, \widetilde{m}_0^{(2)})\widetilde{s}_1 \ldots$ of σ that does not satisfy the request-response objective $\mathsf{RR}(\mathcal{R}')$. We denote by $\widetilde{\mathfrak{m}}_0\widetilde{\mathfrak{m}}_1 \ldots \in \mathfrak{M}^\omega$ the sequence of memory states along the play $\widetilde{\pi}$. We define $\widetilde{\pi}_{|n_2} = \pi_{|n_2}$, i.e., the play $\widetilde{\pi}$ coincides with π up to step n_2. It follows that for any $n \leq n_2$, we have $\widetilde{\mathfrak{m}}_n = \mathfrak{m}_n$. In particular, we have $\widetilde{\mathfrak{m}}_{n_2} = \mathfrak{m}_{n_1}$.

The remainder of the construction is by induction. Let $k \in \mathbb{N}$ and $j \in \{0, \ldots, n_2 - n_1 - 1\}$. We will choose $\widetilde{s}_{n_2+(n_2-n_1)\cdot k+j}$ such that it is equivalent to s_{n_1+j} and $\widetilde{\mathfrak{m}}_{n_2+(n_2-n_1)\cdot k+j} =$

$\mathfrak{m}_{n_1+j}$. The idea to extend $\widetilde{\pi}$ is to follow the cycle in the region abstraction induced by the history $s_{n_1}(m_{n_1}^{(1)}, m_{n_1}^{(2)}) \ldots (m_{n_2-1}^{(1)}, m_{n_2-1}^{(2)}) s_{n_2}$. In practice, to ensure time-divergence of the constructed play, we ensure that the moves $\widetilde{m}_{n_2+(n_2-n_1) \cdot k+j}^{(1)}$ and $\widetilde{m}_{n_2+(n_2-n_1) \cdot k+j}^{(2)}$ are such that $\widetilde{\delta} = \mathsf{delay}(m_{n_2+(n_2-n_1) \cdot k+j}^{(1)}, m_{n_2+(n_2-n_1) \cdot k+j}^{(2)})$ traverses the same regions from $\widetilde{s}_{n_2+(n_2-n_1) \cdot k+j}$ than $\delta = \mathsf{delay}(m_{n_1+j}^{(1)}, m_{n_1+j}^{(2)})$ does from s_{n_1+j}, i.e., $\{[v_{n_1+j} + \delta_{\mathsf{mid}}] \mid 0 \leq \delta_{\mathsf{mid}} \leq \delta\} = \{[\widetilde{v} + \delta_{\mathsf{mid}}] \mid 0 \leq \delta_{\mathsf{mid}} \leq \widetilde{\delta}\}$ where v_{n_1+j} and $\widetilde{v}$ denote the clock valuations in s_{n_1+j} and in $\widetilde{s}_{n_2+(n_2-n_1) \cdot k+j}$ respectively.

We only provide the construction of $\widetilde{m}_{n_2}^{(1)}$, $\widetilde{m}_{n_2}^{(2)}$, $\widetilde{s}_{n_2+1}$ and $\widetilde{\mathfrak{m}}_{n_2+1}$ (i.e., case $k = 0$ and $j = 0$) for the sake of readability. Other cases are handled similarly. We define $\widetilde{m}_{n_2}^{(1)} = \alpha_{\mathsf{mov}}(\widetilde{\mathfrak{m}}_{n_2}, \widetilde{s}_{n_2}) = \alpha_{\mathsf{mov}}(\mathfrak{m}_{n_1}, \widetilde{s}_{n_2})$ to ensure consistency of $\widetilde{\pi}$ with σ. To define $\widetilde{m}_{n_2}^{(2)}$, we distinguish two cases depending on which player is responsible for the transition in π at step n_1.

Assume first that $s_{n_1} \xrightarrow{m_{n_1}^{(1)}} s_{n_1+1}$ holds. Then we let $\widetilde{m}_{n_2}^{(1)}$ be any $\mathcal{P}_2$ move enabled in $\widetilde{s}_{n_2}$ with a delay greater than or equal to that of $\widetilde{m}_{n_1}^{(1)}$. Let $\widetilde{s}_{n_2+1}$ be the unique state such that $\widetilde{s}_{n_2} \xrightarrow{\widetilde{m}_{n_1}^{(1)}} \widetilde{s}_{n_2+1}$ holds. Because σ is a finite-memory region strategy, the equivalence $\widetilde{s}_{n_2+1} \equiv_{\mathcal{A}} s_{n_1+1}$ is ensured and the same regions are traversed from s_{n_1} and $\widetilde{s}_{n_2+1}$ in π and $\widetilde{\pi}$ respectively. It follows from $\mathfrak{m}_{n_1} = \widetilde{\mathfrak{m}}_{n_2}$ and $s_{n_1} \equiv_{\mathcal{A}} \widetilde{s}_{n_2}$ that $\mathfrak{m}_{n_1+1} = \widetilde{\mathfrak{m}}_{n_2+1}$. This closes this case of the inductive step.

Now, assume that $s_{n_1} \xrightarrow{m_{n_1}^{(1)}} s_{n_1+1}$ does not hold. In this case, the move of $\mathcal{P}_2$ is responsible for the transition at step n_1 in π. Let $\delta = \mathsf{delay}(m_{n_1}^{(2)})$ and let v_{n_1} and $\widetilde{v}_{n_2}$ denote the clock valuations in state s_{n_1} and $\widetilde{s}_{n_2}$ respectively. We choose $\widetilde{m}_{n_2}^{(2)} = (\widetilde{\delta}, \mathsf{action}(m_{n_1}^{(2)}))$ for some $\widetilde{\delta} \leq \mathsf{delay}(\widetilde{m}_{n_1}^{(1)})$ such that $\widetilde{v}_{n_2} + \widetilde{\delta} \in [v_{n_1} + \delta]$ and $\{[v_{n+j} + \delta_{\mathsf{mid}}] \mid 0 \leq \delta_{\mathsf{mid}} \leq \delta\} = \{[\widetilde{v}_{n_2} + \delta_{\mathsf{mid}}] \mid 0 \leq \delta_{\mathsf{mid}} \leq \widetilde{\delta}\}$; one such delay exists because the moves $m_{n_1}^{(1)}$ and $\widetilde{m}_{n_2}^{(1)}$ traverse the same regions from s_{n_1} and $\widetilde{s}_{n_2}$ respectively (σ is a finite-memory region strategy), and the region $[v_{n_1} + \delta]$ has the region $[v_{n_1} + \mathsf{delay}(m_{n_1}^{(1)})]$ as a successor.

Let $\widetilde{s}_{n_2+1}$ be the unique state such that $\widetilde{s}_{n_2} \xrightarrow{\widetilde{m}_{n_2}^{(2)}} \widetilde{s}_{n_2+1}$. By choice of $\widetilde{m}_{n_2}^{(2)}$, we have $\widetilde{s}_{n_2+1} \in \mathsf{JD}(\widetilde{s}_{n_2}, \widetilde{m}_{n_2}^{(1)}, \widetilde{m}_{n_2}^{(2)})$. Furthermore, because guard satisfaction is uniform within a region and resets preserve regions, it follows that $\widetilde{s}_{n_2+1} \equiv_{\mathcal{A}} s_{n_1+1}$. Finally, we must have $\mathfrak{m}_{n_1+1} = \widetilde{\mathfrak{m}}_{n_2+1}$ for the same reason as in the previous case.

We now argue that $\widetilde{\pi}$ is time-divergent and does not satisfy the request-response objective $\mathsf{RR}(\mathcal{R}')$. Time-divergence follows from the fact that the global clock γ passes an integer bound between indices n_1 and n_2 in π and that all regions traversed between these indices in π are infinitely often traversed in $\widetilde{\pi}$. For the request-response objective, we first remark that for all $n \in \mathbb{N}$, $[\widetilde{s}_n] \notin U$, because all states appearing in $\widetilde{\pi}$ are equivalent to states in π. Hence, requests and responses along $\widetilde{\pi}$ are determined by the sequence of witnessed locations and their priorities. Let $n^\star \in \mathrm{argmin}_{n_0 \leq n \leq n_2} p_k(\ell_n)$. From index $n^\star$ in $\widetilde{\pi}$, no priority smaller than $p_k(\ell_{n^\star})$ appears on dimension k, and this priority is odd. This shows that some request goes unanswered in $\widetilde{\pi}$, i.e., $\widetilde{\pi} \notin \mathsf{RR}(\mathcal{R}')$, contradicting the fact that σ is winning.

◀

▶ **Remark 16.** The proof of Lemma 15 can be adapted to show that if a state is winning for an arbitrary request-response objective $\mathsf{RR}(\mathcal{R})$, then it is winning for a bounded variant thereof, in which we require that the delay between requests and responses along a play be bounded by some integer.

It follows from Lemma 15 that any state winning for the objective $\mathsf{RR}(\mathcal{R}(p))$ is also

winning for some generalized direct fixed timed window objective, thus for the generalized direct bounded timed window objective. A consequence is that one can use the synthesis algorithm for games with request-response objectives to construct winning strategies for the generalized direct bounded timed window objective from these states.

It remains to argue that states that are winning for the generalized bounded window objective are also winning for the request-response objective. This follows immediately from the inclusion $\mathsf{GDBTW}(p) \subseteq \mathsf{RR}(\mathcal{R}(p))$: if a play satisfies $\mathsf{GDBTW}(p)$, there must be good windows (of bounded size) at all times and on all dimensions along a play, implying that all odd priorities are always followed by smaller even priorities. We obtain the following result.

▶ **Theorem 17.** *Let* $\lambda = 8 \cdot |L| \cdot |\mathsf{Reg}| \cdot (\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^{\mathsf{K}} \cdot \mathsf{K} + 3$. *The sets of winning states for the objectives* $\mathsf{GDFTW}(p, \lambda)$, $\mathsf{GDBTW}(p)$ *and* $\mathsf{RR}(\mathcal{R}(p))$ *coincide. Furthermore, there exists a finite-memory region strategy that is winning for all three objectives from any state in these sets.*

Proof. We first argue that from the set of winning states for $\mathsf{RR}(\mathcal{R}(p))$, there exists a strategy winning for all three objectives at once. Lemma 14 ensures that there exists a finite-memory region strategy $\sigma^{\mathcal{M}}$ induced by a Mealy machine with $4 \cdot (\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^{\mathsf{K}} \cdot \mathsf{K}$ states and proposing delays of at most 1 suffices to win for $\mathsf{RR}(\mathcal{R}(p))$. It follows from Lemma 15 that $\sigma^{\mathcal{M}}$ is winning for the objectives $\mathsf{GDFTW}(p, \lambda)$ and $\mathsf{GDBTW}(p)$ from any state from which $\mathcal{P}_1$ has a winning strategy for $\mathsf{RR}(\mathcal{R}(p))$.

It follows from the above that the set of winning states for $\mathsf{RR}(\mathcal{R}(p))$ is a subset of the set of winning states of the two window objectives. Furthermore, the inclusion $\mathsf{GDFTW}(p, \lambda) \subseteq \mathsf{GDBTW}(p)$ implies that any state winning for the fixed objective is also winning for the bounded objective. To end the proof, it suffices to show that the inclusion $\mathsf{GDBTW}(p) \subseteq \mathsf{RR}(\mathcal{R}(p))$ holds to obtain that the set of winning states for the bounded window objective is included in that of the request-response objective.

Let $\pi = s_0(m_0^{(1)}, m_0^{(2)})s_1 \ldots \in \mathsf{GDBTW}(p)$ be a play conforming to the generalized direct bounded timed window objective. Let $n \in \mathbb{N}$ such that $s_n \in \mathsf{Rq}$ for some $(\mathsf{Rq}, \mathsf{Rp}) \in \mathcal{R}(p)$. There is some dimension $k \in \{1, \ldots, \mathsf{K}\}$ such that $\mathsf{Rq} = p_k^{-1}(j) \times \mathsf{Reg}$ for some odd priority j. By definition, there is some $\lambda \in \mathbb{N}$ such that $\pi \in \mathsf{DFTW}(p_k, \lambda)$, which implies $\pi_{n\rightarrow} \in \mathsf{TGW}(p_k, \lambda)$. It follows immediately from the definition of $\mathsf{TGW}(p_k, \lambda)$ that there exists some $n' > n$ such that the priority of the location of $s_{n'}$ on dimension k is even and smaller than j, i.e., $[s_{n'}] \in \mathsf{Rp}$. This shows that π satisfies the request-response objective, and ends the proof. ◀

We conclude this section by determining the time complexity of solving the realizability problem for direct bounded timed window objectives. We produce a request-response objective with $\mathsf{K} \cdot \lfloor \frac{\mathsf{D}}{2} \rfloor$ pairs, i.e., our reduction is in polynomial time. In light of Lemma 14, we obtain that the overall reduction-based algorithm described above for realizability in TGs with direct bounded timed window objectives is in exponential time.

▶ **Theorem 18.** *The realizability problem for TGs with generalized direct bounded timed window objectives is in* EXPTIME.

Proof. It takes time $\mathcal{O}((\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^{\mathsf{K}} \cdot \mathsf{K} \cdot |L| \cdot |\mathsf{Reg}|)$ to construct a DBA encoding $\mathsf{RR}(\mathcal{R}(p))$ (the factor $|L| \cdot |\mathsf{Reg}|$ comes from the construction of transitions), and by Lemma 14, it takes time $\mathcal{O}((|L| \cdot |\mathsf{Reg}| \cdot (\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^{\mathsf{K}} \cdot \mathsf{K}))^3)$ to solve the request-response game. Overall, we need exponential time to solve the game. ◀

5.2   Indirect bounded timed window objective

In this section, we show the EXPTIME-membership of the realizability problem for the generalized bounded timed window objective. To this end, we provide a fixed-point algorithm to solve these games. At each step of the algorithm, we compute the set of winning states for a given request-response objective.

The structure of the section is as follows. We open the section by presenting the algorithm and proving its termination in Section 5.2.1. The correctness of the algorithm is shown in Section 5.2.2. Section 5.2.3 establishes that the algorithm terminates in exponential time.

5.2.1   An algorithm for solving bounded timed window games

We provide a fixed-point algorithm to compute the set of winning states for the bounded timed window objective. We utilize request-response objectives as in the direct case.

The algorithm behaves as follows. We start by computing the winning set W^1 for the direct objective via the request-response objective $\mathsf{RR}(\mathcal{R}(p))$; we obtain in this way a subset of the set of winning states, because $\mathsf{GDBTW}(p) \subseteq \mathsf{GBTW}(p)$. It follows from the prefix-independence of $\mathsf{GBTW}(p)$ that $\mathcal{P}_1$ can extend any play that reaches W^1 into a winning play. Hence, we can compute a larger subset W^2 of the set of winning states of $\mathcal{P}_1$ by changing our request-response pairs in such a way that reaching W^1 clears all requests.

This set W^2 is a subset of the set of winning states; intuitively if $\mathcal{P}_1$ uses a winning strategy for the simplified request-response objective from W^2 and the play does not reach W^1, the outcome satisfies the winning condition for the direct objective $\mathsf{GDBTW}(p)$ by Lemma 15 with $U = \{[s] \mid s \in W^1\}$. This reasoning can be repeated inductively: we update the request-response objective so that states in W^2 clear all requests. We continue until a fixed point is reached; the set of states W obtained this way is a set of states from which $\mathcal{P}_1$ has a winning strategy for the objective $\mathsf{GBTW}(p)$.

We now formally present the algorithm. The steps of the algorithm are as follows. First, we construct the family of request-response pairs $\mathcal{R}(p)$. After this initialization, the algorithm enters a loop, in which we repeatedly solve request-response games. We modify the request-response pairs at each step by marking regions that were in the latest computed winning set as responses for all possible requests. Note that at each step, we always have K-chain-response families. The algorithm terminates when the set of winning states no longer grows. The procedure is summarized in Algorithm 1, in which we assume a sub-routine SolveRR which given a TG and a K-chain-response family $\mathcal{R}$, outputs the set of winning states in the TG for the objective $\mathsf{RR}(\mathcal{R})$.

We now move on to the termination of Algorithm 1. It is known that the set of winning states for ω-regular region objectives in TGs are unions of state regions (Theorem 1). Hence, it suffices to show that the sequence of sets $(W^k)_{k \in K}$ computed at each step of the algorithm is non-decreasing to obtain a proof of termination, as there are finitely many state regions. Let us note that it is due to this property that we refer to Algorithm 1 as a fixed-point algorithm. Intuitively, the result holds because we simplify the request-response objectives from one iteration to the next.

▶ **Lemma 19.** *The sequence of sets $(W^k)_{k \in K}$ computed in the loop of Algorithm 1 is non-decreasing. As a consequence, Algorithm 1 terminates.*

Proof. We show the first statement of the lemma. We proceed by induction. We trivially have $W^0 \subseteq W^1$ given that $W^0 = \emptyset$. Let us now take $k \in K$, $k < \sup K$, and show that $W^k \subseteq W^{k+1}$. Let $\mathcal{R}^k$ and $\mathcal{R}^{k+1}$ respectively denote the family of request-response pairs

■ **Algorithm 1** Computing the set of winning states for $\mathsf{BTW}(p)$

Data: A TG $\mathcal{G} = (\mathcal{A}, \Sigma_1, \Sigma_2)$, a multi-dimensional priority function p over $\mathcal{A}$.

$k \leftarrow 0$;
$W^0 \leftarrow \emptyset$;
$\mathcal{R} \leftarrow \mathcal{R}(p)$;
repeat
   | $k \leftarrow k + 1$;
   | $W^k \leftarrow \mathsf{SolveRR}(\mathcal{G}, \mathcal{R})$;
   | **for** $(\mathsf{Rq}, \mathsf{Rp}) \in \mathcal{R}$ **do**
      | | $\mathsf{Rq} \leftarrow \mathsf{Rq} \setminus \{[s] \in L \times \mathsf{Reg} \mid [s] \subseteq W^k\}$;
      | | $\mathsf{Rp} \leftarrow \mathsf{Rp} \cup \{[s] \in L \times \mathsf{Reg} \mid [s] \subseteq W^k\}$;
until $W^k \setminus W^{k-1} = \emptyset$;
return W^k;

---

from which W^k and W^{k+1} were computed. To obtain $W^k \subseteq W^{k+1}$, it suffices to show that $\mathsf{RR}(\mathcal{R}^k) \subseteq \mathsf{RR}(\mathcal{R}^{k+1})$; W^k and W^{k+1} are the respective winning sets for these objectives.

Let $s_0 s_1 \ldots \in \mathsf{RR}(\mathcal{R}^k)$ be an infinite sequence of states. We must show that $s_0 s_1 \ldots \in \mathsf{RR}(\mathcal{R}^{k+1})$. Let $(\mathsf{Rq}^{k+1}, \mathsf{Rp}^{k+1}) \in \mathcal{R}^{k+1}$ be a request-response pair. Assume there exists $i \in \mathbb{N}$ be such that $s_i \in \mathsf{Rq}^{k+1}$. It follows from the innermost loop of the algorithm that there is some request-response pair $(\mathsf{Rq}^k, \mathsf{Rp}^k) \in \mathcal{R}^k$ such that $\mathsf{Rq}^{k+1} \subseteq \mathsf{Rq}^k$ and $\mathsf{Rp}^{k+1} \supseteq \mathsf{Rp}^k$. It follows from $s_0 s_1 \ldots \in \mathsf{RR}(\mathcal{R}^k)$ and $\mathsf{Rq}^{k+1} \subseteq \mathsf{Rq}^k$ that there is some $j \geq i$ such that $s_j \in \mathsf{Rp}^k \subseteq \mathsf{Rp}^{k+1}$. This shows that $s_0 s_1 \ldots \in \mathsf{RR}(\mathcal{R}^{k+1})$. This ends the argument that $(W^k)_{k \in K}$ is non-decreasing.

It remains to show that Algorithm 1 terminates. Each W^k, $k \in K$, is a union of state regions. There are finitely many state regions and we have shown $(W^k)_{k \in K}$ to be non-decreasing, thus it follows the sequence eventually reaches a fixed point, i.e., the algorithm terminates. ◀

5.2.2 Correctness of the fixed-point algorithm

In this section, we prove that the set W returned by Algorithm 1 is the set of winning states for $\mathcal{P}_1$ in the TG $\mathcal{G}$ for the objective $\mathsf{GBTW}(p)$. We establish the stronger claim that $\mathcal{P}_1$ has a strategy that is winning for some generalized fixed timed window objective from W.

The proof is done in two steps. First, we show that Algorithm 1 outputs a subset of the set of winning states of $\mathcal{P}_1$ on which finite-memory region strategies suffice. Second, to end the proof of correctness, we show that the complement of the returned set is not winning for $\mathsf{GBTW}(p)$.

Let us argue that $\mathcal{P}_1$ has a winning strategy from any state in the set W returned by Algorithm 1. The set W is organized in layers: each set $W^k \setminus W^{k-1}$ is one such layer. We can construct winning strategies by exploiting this layered structure. In the lowermost layer W^1, we have the winning set for $\mathsf{GDBTW}(p)$, which is also winning for a fixed objective (Theorem 17); any winning strategy for the direct objective is trivially winning for the indirect objective.

Higher layers are handled inductively. Given some layer, e.g., $W^k \setminus W^{k-1}$, one argues that $\mathcal{P}_1$ wins by constructing a strategy that changes its behavior when a lower layer is reached: as long as the layer does not change, $\mathcal{P}_1$ plays a winning strategy for the current request-response objective, and should a deeper layer be reached, $\mathcal{P}_1$ wins by forgetting

the history and switching to a winning strategy in this deeper layer. All outcomes of this strategy are winning by prefix-independence of the objective; once the layer index no longer decreases, Lemma 15 ensures that that some generalized direct fixed objective is satisfied if time diverges.

By choosing finite-memory region winning strategies for each request-response objective in the construction of the layered winning strategy, we can even show that finite-memory region strategies suffice for winning in W. The idea is to keep track of the current layer in memory, and whenever the layer of the current state is lower than that in the memory, we act as though we had just started the play in the current state. The following lemma and its proof formalize the explanations above.

▶ **Lemma 20.** *Let $\lambda = 8 \cdot |L| \cdot |\mathsf{Reg}| \cdot (\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^{\mathsf{K}} \cdot \mathsf{K} + 3$. The set W provided by Algorithm 1 is a subset of the set of winning states of $\mathcal{P}_1$ for the objective $\mathsf{GFTW}(p, \lambda)$ and finite-memory region strategies suffice for winning from any state in W.*

Proof. We first describe a Mealy machine encoding a winning finite-memory region strategy of $\mathcal{P}_1$, and then prove it indeed encodes a winning strategy.

Let K denote the set of positive integers such that $W^k \setminus W^{k-1}$ is non-empty. For each $k \in K$, let $\mathcal{R}^k$ be the family of request-response pairs from which W^k was computed, and let $\mathcal{M}^k = (\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}}^k, \alpha_{\mathsf{mov}}^k)$ be a Mealy machine encoding a finite-memory region strategy for $\mathcal{P}_1$ on W^k for the objective $\mathsf{RR}(\mathcal{R}^k)$, proposing delays of at most 1 (Lemma 14) with $4 \cdot (\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^{\mathsf{K}} \cdot \mathsf{K}$ states. We can assume that these Mealy machines all share the same state space $\mathfrak{M}$. For any state $s \in W$, we let $\mathsf{e}([s]) = \min\{k \in K \mid [s] \subseteq W^k\}$ denote the earliest index $k \in K$ such that $s \in W^k$.

We will consider the Mealy machine $\mathcal{M} = (\mathfrak{M} \times K, (\mathfrak{m}_{\mathsf{init}}, \max K), \alpha_{\mathsf{up}}, \alpha_{\mathsf{mov}})$ where the update function $\alpha_{\mathsf{up}} \colon \mathfrak{M} \times K \times \mathsf{Reg} \to \mathfrak{M}$ is defined, for all $\mathfrak{m} \in \mathfrak{M}$, $k \in K$ and $s \in S$, by

$$\alpha_{\mathsf{up}}(\mathfrak{m}, k, [s]) = \begin{cases} (\alpha_{\mathsf{up}}^k(\mathfrak{m}, [s]), k) & \text{if } s \notin W \text{ or } \mathsf{e}([s]) \geq k \\ (\alpha_{\mathsf{up}}^{\mathsf{e}([s])}(\mathfrak{m}_{\mathsf{init}}, [s]), \mathsf{e}([s])) & \text{otherwise,} \end{cases}$$

and $\alpha_{\mathsf{mov}} \colon \mathfrak{M} \times K \times \mathsf{Reg} \to M_1$ is defined, for all $\mathfrak{m} \in \mathfrak{M}$, $k \in K$ and $s \in S$, by

$$\alpha_{\mathsf{mov}}(\mathfrak{m}, k, [s]) = \begin{cases} \alpha_{\mathsf{mov}}^k(\mathfrak{m}, [s]) & \text{if } s \notin W \text{ or } \mathsf{e}([s]) \geq k \\ \alpha_{\mathsf{mov}}^{\mathsf{e}([s])}(\mathfrak{m}_{\mathsf{init}}, [s]) & \text{otherwise.} \end{cases}$$

Intuitively, $\mathcal{M}$ encodes a strategy that plays a winning strategy of W^k as long as the play remains in W^k, and whenever the plays visits a state in some $W^{k'}$ with $k' < k$, forgets the past and switches to a winning strategy in $W^{k'}$.

We now show that $\mathcal{M}$ encodes a strategy that is winning from every state in W. Let $\pi = s_0(m_0^{(1)}, m_0^{(2)})s_2 \ldots$ be an outcome of the strategy induced by $\mathcal{M}$ starting in some state of W, and let $((\mathfrak{m}_n, k_n))_{n \in \mathbb{N}}$ be the sequence of memory states such that $(\mathfrak{m}_0, k_0) = (\mathfrak{m}_{\mathsf{init}}, \max K)$ and for all $n \in \mathbb{N}$, $(\mathfrak{m}_{n+1}, k_{n+1}) = \alpha_{\mathsf{up}}(\mathfrak{m}_n, k_n, [s_n])$. We first argue that there exists some $k \in K$ such that π has a suffix that starts in $W^k \setminus W^{k-1}$ and that is consistent with the strategy induced by $\mathcal{M}^k$.

By construction of α_{up}, the sequence $(k_n)_{n \in \mathbb{N}}$ is a non-increasing sequence of non-negative integers, hence it must stabilize at some point to some $k \in K$. We now argue that π has a suffix starting in $W^k \setminus W^{k-1}$ and consistent with the strategy induced by $\mathcal{M}^k$. We distinguish two cases, depending on whether $k = k_0$ or not.

First, assume that $k < k_0 = \max K$. Let $n_0 = \min\{n \in \mathbb{N} \mid k_n = k\} - 1$. By definition of α_{up}, it must be the case that $\mathsf{e}([s_{n_0}]) = k$, i.e., $s_{n_0} \in W^k \setminus W^{k-1}$. The suffix $\pi_{n_0 \to}$ is consistent

with the strategy encoded by $\mathcal{M}^k$: the first move in $\pi_{n_0 \to}$ is given by $\alpha_{\mathsf{mov}}^k(\mathfrak{m}_{\mathsf{init}}, [s_{n_0}])$ by definition of α_{mov}, and for later steps, it follows from the fact that $(k_n)_{n > n_0}$ is a constant sequence and the definitions of α_{up} and α_{mov}. Indeed, memory updates and move proposals are performed as they would be in $\mathcal{M}^k$: the component in K of memory states of $\mathcal{M}$ is disregarded.

Now, assume that $k = k_0 = \max K$. It follows from the definition of α_{mov} that π is consistent with the strategy induced by $\mathcal{M}^k$. Furthermore, by definition of α_{up}, it must be the case that no state in W^{k-1} has been visited, i.e., π starts in $W^k \setminus W^{k-1}$. In this case, π itself is a play consistent with $\mathcal{M}^k$ that starts in $W^k \setminus W^{k-1}$. We let $n_0 = 0$ so as to treat both cases simultaneously in the remainder of the proof; note that $\pi = \pi_{0 \to}$.

We now prove that $\pi \in \mathsf{WC}_1(\mathsf{GFTWP}(p, \lambda))$. The definition of the indirect window objectives imply that it suffices to show that $\pi_{n_0 \to} \in \mathsf{WC}_1(\mathsf{GDFTWP}(p, \lambda))$. If $\pi_{n_0 \to}$ is time-convergent, then it must be blameless for $\mathcal{P}_1$ because it is the outcome of a winning strategy (the strategy induced by $\mathcal{M}^k$). Assume that $\pi_{n_0 \to}$ is time-divergent. By Lemma 19, we obtain $W^{k-1} = \bigcup_{k' \le k-1} W^{k'}$. We can therefore apply Lemma 15 with $U = \{[s] \mid s \in W^{k-1}\}$ and $\mathcal{M}^k$ to obtain that $\pi_{n_0 \to}$ satisfies $\mathsf{GDFTW}(p, \lambda))$. We have shown that the strategy induced by $\mathcal{M}$ is winning from every state of W, ending the proof. ◄

Lemma 20 asserts that all states in the output W of Algorithm 1 are winning for some generalized fixed timed window objective, hence for the generalized bounded timed window objective. To finish the proof of correctness of the algorithm, it remains to show that states outside of W are not winning for the generalized bounded timed window objective. The idea is to show that for any strategy of $\mathcal{P}_1$, there is some losing outcome when starting from $S \setminus W$.

We use the fact that states in $S \setminus W$ are losing for some request-response objective where states in W answer all pending requests. It follows that any losing time-divergent outcome eventually stays in $S \setminus W$. We can inductively construct an outcome that violates the bounded timed window objective in stages as follows. At stage n, we forget about the past and follow a play that is losing for the request-response objective, while remaining consistent with the strategy of $\mathcal{P}_1$ fixed beforehand. We follow this play until some request is left pending for at least n time units, and then move on to the next stage. This constructs some losing outcome of $\mathcal{P}_1$'s strategy because requests come from odd priorities: an unanswered request for n time units implies the existence of a window that is not good within n time units on some dimension. Because there are finitely many dimensions, this outcome cannot satisfy the bounded timed window objective on at least one dimension, and it follows that $\mathcal{P}_1$'s strategy is not winning. We formalize this construction in the following proof.

▶ **Lemma 21.** *Let W denote the set provided by Algorithm 1. From every state in $S \setminus W$, $\mathcal{P}_1$ has no winning strategy for the objective* $\mathsf{GBTW}(p)$.

Proof. Let $\mathcal{R}$ be the request-response family $\{(\mathsf{Rq} \setminus [W], \mathsf{Rp} \cup [W]) \mid (\mathsf{Rq}, \mathsf{Rp}) \in \mathcal{R}(p)\}$ appearing in the last iteration of Algorithm 1, where $[W] = \{[s] \in L \times \mathsf{Reg} \mid s \in W\}$ denotes the set of state regions in W. The set W is the set of winning states of $\mathcal{P}_1$ for the request-response objective $\mathsf{RR}(\mathcal{R})$. It follows that from each state in $S \setminus W$, $\mathcal{P}_1$ has no winning strategy for this objective.

Let $s \in S \setminus W$. We must show that $\mathcal{P}_1$ has no winning strategy for $\mathsf{GBTW}(p)$ from s. Fix a strategy σ of $\mathcal{P}_1$. If σ has some time-convergent outcome that is not blameless for $\mathcal{P}_1$, σ cannot be a winning strategy. In the sequel, we assume that all time-convergent outcomes of σ are blameless for $\mathcal{P}_1$.

We construct an outcome of σ from s by inductively extending histories. We will denote the history after step $n \in \mathbb{N}$ of the construction by h_n. The inductive assumptions we rely on is that h_n ends in some state of $S \setminus W$, and that h_n is consistent with σ. The play obtained in the limit of the construction will be an outcome of σ from s. To ensure that this outcome violates $\mathsf{GBTW}(p)$, we construct our histories as follows: for $n \geq 1$, in the history appended to h_{n-1} so as to obtain h_n, on some dimension, there is some odd priority that was not followed by any smaller even priority within n time units. The resulting play violates $\mathsf{GBTW}(p)$: no matter the suffix taken, even if all windows along it are good on all dimensions, there is no bound on their size over all dimensions, hence there is some dimension on which there is no bound. Furthermore, this play is also time-divergent; at step n of the construction, a history in which at least n time units elapse is appended.

We introduce some notation. Given a history $h = s_0(m_0^{(1)}, m_0^{(2)}) \ldots (m_{k-1}^{(1)}, m_{k-1}^{(2)}) s_k \in \mathsf{Hist}(\mathcal{G})$ and some history or play $\pi = s_k(m_k^{(1)}, m_k^{(2)}) \ldots (m_{k'-1}^{(1)}, m_{k'-1}^{(2)}) s_{k'} \ldots \in \mathsf{Hist}(\mathcal{G}) \cup \mathsf{Plays}(\mathcal{G})$ where the last state of h is the first state of π, we let $h \cdot \pi$ denote the play or history $s_0(m_0^{(1)}, m_0^{(2)}) \ldots (m_{k-1}^{(1)}, m_{k-1}^{(2)}) s_k(m_k^{(1)}, m_k^{(2)}) \ldots (m_{k'-1}^{(1)}, m_{k'-1}^{(2)}) s_{k'} \ldots$ obtained by concatenating h and π and disregarding the repeated state.

We let $h_0 = s$, which trivially satisfies the inductive assumptions. Now, assume that h_n has been constructed, and let $s_n = \mathsf{last}(h_n)$. We consider a strategy σ_n such that for any history $h \in \mathsf{Hist}(\mathcal{G})$ starting in s_n, $\sigma_n(h) = \sigma(h_n \cdot h)$. The strategy σ_n uses the actions which would have been proposed by σ if we had seen h_n prior to the input history.

Because s_n is losing for $\mathsf{RR}(\mathcal{R})$, there exists some outcome π_n of σ_n starting in s_n such that $\pi_n \notin \mathsf{WC}_1(\mathsf{RR}(\mathcal{R}))$. By choice of σ_n, the play $h_n \cdot \pi_n$ is an outcome of σ. The play π_n must be time-divergent, otherwise the play $h_n \cdot \pi_n$ would not be blameless for $\mathcal{P}_1$, which contradicts the assumption that all time-convergent outcomes of σ are blameless for $\mathcal{P}_1$. We therefore have that π_n is time-divergent and $\pi_n \notin \mathsf{RR}(\mathcal{R})$.

There is some request along π_n that is never followed by a response. From states in W, all requests are answered, and hence there are no occurrences of W after this request. Furthermore, because π_n is time-divergent, there is some prefix $h(\pi_n)$ of π_n such that at least $n + 1$ time units elapse between the unanswered request and the last state of $h(\pi_n)$. It suffices to choose $h_{n+1} = h_n \cdot h(\pi_n)$ to obtain all desired properties.

This concludes the construction of a time-divergent outcome of σ that violates $\mathsf{GBTW}(p)$. We have thus shown that σ is not a winning strategy, and therefore that s is not in the set of winning states of $\mathcal{P}_1$ for $\mathsf{GBTW}(p)$. ◀

We summarize the results of the section in the following theorem. On the one hand, Lemma 20 implies that the set returned by Algorithm 1 is a subset of the set of winning states for $\mathsf{GBTW}(p)$ on which finite-memory region strategies suffice, and such a strategy can be chosen as winning for some generalized fixed timed window objective. On the other hand, Lemma 21 implies that $\mathcal{P}_1$ has no winning strategy on the complement of the set computed by Algorithm 1 for any fixed timed window objective. We obtain the following theorem.

▶ **Theorem 22.** *Let $\lambda = 8 \cdot |L| \cdot |\mathsf{Reg}| \cdot (\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^{\mathsf{K}} \cdot \mathsf{K} + 3$. The sets of winning states for the objectives $\mathsf{GFTW}(p, \lambda)$ and $\mathsf{GBTW}(p)$ coincide. Furthermore, there exists a finite-memory region strategy that is winning for both objectives from any state in these sets of winning states.*

5.2.3 Complexity of the fixed-point algorithm

We conclude this section by determining the computational complexity of Algorithm 1. In the worst case, there are as many iterations as there are state regions. While the complexity

of solving the request-response games is in EXPTIME, we still obtain an EXPTIME algorithm because the exponential terms are multiplied rather than stacked. We obtain the following result.

▶ **Theorem 23.** *The realizability problem for bounded timed window objectives is in EXPTIME.*

Proof. We show that Algorithm 1 runs in exponential time to finish this proof. By Lemma 14 the subroutine SolveRR($\mathcal{R}$) runs in time $\mathcal{O}((|L| \cdot |\mathsf{Reg}| \cdot (\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^\mathsf{K} \cdot \mathsf{K})^3)$ (the time to solve the TG dominates that of the DPA construction). The innermost loop iterates $\lfloor \frac{\mathsf{D}}{2} \rfloor \cdot \mathsf{K}$ times. The outermost loop iterates at most $|L| \cdot |\mathsf{Reg}|$ times. By combining all of these complexities appropriately, one obtains a time complexity in $\mathcal{O}((|L| \cdot |\mathsf{Reg}| \cdot (\lfloor \frac{\mathsf{D}}{2} \rfloor + 1)^\mathsf{K} \cdot \mathsf{K})^4)$. ◀

6 Lower bounds and completeness

In this section, we establish the PSPACE and EXPTIME completeness of the verification and realizability problems for the direct and indirect bounded timed window objectives. In light of Theorems 13, 18 and 23 that assert membership of these problems in these complexity classes, we need only establish hardness to obtain completeness. In the remainder of this section, we no longer distinguish direct and indirect cases; arguments are the same in both cases.

We will consider the verification and realizability problems for safety objectives to establish hardness. The verification problem for safety objectives is PSPACE-complete [2], and the realizability problem for safety objectives is EXPTIME-complete (as a consequence of the EXPTIME-completeness of the safety control problem [27]).

It was shown in [30] that there exists a polynomial-time reduction from the verification and realizability problems for safety objectives to these respective problems for fixed timed window objectives. Furthermore, the reduction works no matter the bound on the size of windows in the definition of the fixed objective, i.e., the two problems for safety objectives are reducible in polynomial time to their counterpart for the objectives $\mathsf{FDTW}(p, \lambda)$ or $\mathsf{FTW}(p, \lambda)$ for any $\lambda \geq 1$ (for some appropriate priority function p) with a construction independent of λ. We argue that these same reductions are suitable to establish hardness of the studied problems with bounded timed window objectives.

An intuitive sketch of the reductions follows. They are similar for both the verification and realizability problems; we modify the TA in the same way in both cases, and make no changes to the partition of actions in TGs. Let $\mathcal{A} = (L, \ell_{\mathsf{init}}, C, \Sigma, I, E)$ be a TA. Fix $F \subseteq L$. Recall that the safety objective for F requires that no location of F ever be visited.

The reduction consists in deriving a TA $\mathcal{A}'$ from $\mathcal{A}$ in which locations are augmented with a Boolean value indicating whether F has been previously visited. Edges of $\mathcal{A}$ are replicated in $\mathcal{A}'$. These edges do not update the Boolean value, unless they target some location in F, in which case the Boolean value is changed to indicate F has been visited. The initial location $(\ell_{\mathsf{init}}, b)$ of $\mathcal{A}'$ indicates that F has been visited if and only if $\ell_{\mathsf{init}} \in F$. To define the window objectives, we use a priority function assigning 0 (respectively 1) to locations indicating F has not been visited (respectively has been visited). Intuitively, correctness of the reduction follows from the fact that if F is never visited, then only the priority 0 appears, and otherwise, from some point on, only the priority 1 appears. In the former case, any variant of timed window parity objectives are satisfied trivially, and in the latter, they are trivially violated.

Formally, we can also derive hardness for the verification and realizability problems for the bounded timed window objectives as follows. We have established that the verification and

realizability problem for bounded timed window objectives are equivalent to some instance of verification and realizability problems respectively for some fixed timed window objective on the same TA or TG (Corollaries 8 and 10 for verification and Theorems 17 and 22 for realizability). Because the reduction above is known to work for fixed objectives for any bound λ, it follows that the verification and realizability problems for safety objectives are reducible in polynomial time to the verification and realizability problems for the bounded timed window objectives, yielding PSPACE and EXPTIME-hardness of these problems in the one-dimensional case. We obtain the following result.

▶ **Theorem 24.** *The verification problem for generalized direct and indirect bounded timed window objectives is PSPACE-complete and the realizability problem for generalized direct and indirect bounded timed window objectives is EXPTIME-complete.*

7 Comparing window objectives in timed and untimed settings

In this section, we provide a short comparison of timed window objectives. We compare the timed and untimed settings, as well as the fixed and bounded settings. A summary of the complexity classes for each respective problem is provided in Table 1. We fix a TG $\mathcal{G} = (\mathcal{A}, \Sigma_1, \Sigma_2)$ with $\mathcal{A} = (L, \ell_{\mathsf{init}}, C, \Sigma_1 \cup \Sigma_2, I, E)$ for the upcoming explanations.

		Single dimension	Multiple dimensions
Timed automata	Fixed [30]	PSPACE-complete	PSPACE-complete
	Bounded	**PSPACE-complete**	**PSPACE-complete**
Timed games	Fixed [30]	EXPTIME-complete	EXPTIME-complete
	Bounded	**EXPTIME-complete**	**EXPTIME-complete**
Games (untimed) [14]	Fixed	P-complete	EXPTIME-complete
	Bounded	P-complete	EXPTIME-complete

Table 1 Summary of the complexity classes for problems with window parity objective in timed and untimed settings. Direct and prefix-independent cases are grouped together as their complexity matches. New results are in boldface.

First, let us compare TGs with parity objectives and with window parity objectives by analogy to the setting of untimed games. In the one-dimensional case, in both the fixed and bounded cases, solving untimed games with window parity objectives can be done in polynomial time. Parity games on graphs are widely studied and have recently been shown to be solvable in quasi-polynomial time [16], but are not yet known to be solvable in polynomial time. In many algorithms, the number of priorities is responsible for their high complexity. One-dimensional window parity games provide a polynomial time alternative to parity games; the number of priorities contributes polynomially to the complexity of solving an untimed window parity game.

In the timed setting, TGs with parity objectives can be solved in exponential time [23], and [22] proposes a reduction from parity TGs to untimed parity games; from a TG and a priority function $p \colon L \to \{0, \ldots, \mathsf{D} - 1\}$, they construct a turn-based parity game with $256 \cdot |L| \cdot |\mathsf{Reg}| \cdot |C| \cdot \mathsf{D}$ states and priorities at most $\mathsf{D} + 1$. The solving of parity TGs by means of this reduction nevertheless suffers from the blow-up in the number of priorities in the same way as untimed games. Similarly to the untimed setting, fixed and bounded timed window objectives avoid this issue; the number of priorities only contributes polynomially to the complexity of solving these games.

Now let us move on to a comparison of the fixed and bounded cases. Despite there being no difference in the complexity classes for the two cases, a TG with a generalized direct or indirect fixed timed window objective with K dimensions and bound $\lambda \in \mathbb{N}$ can be solved in time

$$\mathcal{O}\left(\left(|L| \cdot (\mathsf{D}^{\mathsf{K}} + 1) \cdot (|C| + \mathsf{K})! \cdot 2^{|C|+\mathsf{K}} \cdot \prod_{x \in C} (2c_x + 1) \cdot (2\lambda + 1)^{\mathsf{K}} \right)^4 \right)$$

with the approach of [30], where c_x denotes the largest bound to which clock $x \in C$ is compared in clock constraints of $\mathcal{A}$. It follows that the algorithm, for a fixed number of dimensions, is polynomial in the bound on the size of windows (i.e., exponential in the size of its encoding). When solving TGs with bounded timed window objectives, the complexity of the algorithms presented in previous sections is not affected by the potential size of good windows. Because the winning set for a bounded objective coincides with the winning set for some fixed objective, it follows that the algorithms for TGs with bounded objectives can be used to more efficiently solve TGs with fixed objectives with large bounds, by entirely bypassing the bound in question.

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A   Winning strategies in ω-regular timed games

In this section, we present an approach to solving timed games with ω-regular region objectives as a direct extension of the technique of [23] for timed games with ω-regular location objectives, i.e., objectives the satisfaction of which depends only on the sequence of witnessed locations in the same way that region objectives depend only on the sequence of witnessed regions along a play. The main interest of this presentation is to highlight some useful properties of winning strategies in timed games with ω-regular region objectives, namely that finite-memory region strategies suffice for winning. We assume that the objectives are given by deterministic parity automata.

The main ideas are as follows. First, we consider an expanded game in which blamelessness and time-divergence can be encoded as ω-regular conditions. We alter the deterministic parity automaton defining the objective so that it encodes the winning condition itself rather than the objective. We can then compute memoryless region strategies on the (infinite) parity game obtained through the product of the expanded game and expanded parity automaton [23, 24]. The remainder of this section is devoted to showing that we can use these memoryless region strategies to derive a winning finite-memory strategies on the non-expanded TG.

We fix a TG $\mathcal{G} = (\mathcal{A}, \Sigma_1, \Sigma_2)$ where $\mathcal{A} = (L, \ell_{\mathsf{init}}, C, \Sigma_1 \cup \Sigma_2, I, E)$ for this entire section. Recall that we use S and $\rightarrow$ to denote the state space and transition relation of $\mathcal{T}(\mathcal{A})$, and JD for the joint-destination function.

Expanding the state space of the game.   To encode time-divergence and blamelessness as ω-regular conditions, we expand the state space S with two Boolean values, i.e., we consider an expanded state space $\widehat{S} = S \times \{\mathsf{true}, \mathsf{false}\}^2$. Expanded states are of the form $(s, \mathsf{tick}, \mathsf{blame})$, where tick holds if and only if during the previous transition, the global clock γ passes a new integer bound, and blame holds if $\mathcal{P}_1$ is responsible for the latest transition. We extend the joint-destination function so that it handles the additional information. We denote by $\widehat{\mathsf{JD}} \colon \widehat{S} \times M_1 \times M_2 \to 2^{\widehat{S}}$ the expanded joint-destination function, defined as follows. For any expanded state $\widehat{s} = (s, \mathsf{tick}, \mathsf{blame}) \in \widehat{S}$ and moves $m^{(1)} = (\delta^{(1)}, a^{(1)}) \in M_1(s)$ and $m^{(2)} = (\delta^{(2)}, a^{(2)}) \in M_2(s)$ enabled in s, we set

$$\mathsf{JD}(s, m^{(1)}, m^{(2)}) = \begin{cases} \{(s', \mathsf{tick}(s, \delta^{(1)}), \mathsf{true}) \mid s \xrightarrow{m^{(1)}} s'\} & \text{if } \delta^{(1)} < \delta^{(2)} \\ \{(s', \mathsf{tick}(s, \delta^{(2)}), \mathsf{false}) \mid s \xrightarrow{m^{(2)}} s'\} & \text{if } \delta^{(1)} > \delta^{(2)} \\ \{(s', \mathsf{tick}(s, \delta^{(i)}), \mathsf{bl}_1(s, m^{(1)}, s')) \mid s \xrightarrow{m^{(i)}} s', i = 1, 2\} & \text{if } \delta^{(1)} = \delta^{(2)}, \end{cases}$$

where for any $s' = (\ell, v) \in S$ and $\delta \geq 0$, $\mathsf{tick}(s', \delta)$ holds if and only if $\lfloor v(\gamma) \rfloor < \lfloor v(\gamma) + \delta \rfloor$, and $\mathsf{bl}_1(s, m^{(1)}, s')$ holds only if $s \xrightarrow{m^{(1)}} s'$ (i.e., if $\mathcal{P}_1$ is responsible for the transition).

We denote this expanded game by $\widehat{\mathcal{G}}$. The notions of plays, histories, time-divergence, blame, strategies and objectives are defined analogously in $\widehat{\mathcal{G}}$ as they were in regular TGs. We extend state equivalence to the state space of $\widehat{\mathcal{G}}$ by saying that any two states $(\ell, v, \mathsf{tick}, \mathsf{blame})$ and $(\ell', v', \mathsf{tick}', \mathsf{blame}')$ are state-equivalent if $\ell = \ell'$, $v \equiv_{\mathcal{A}} v$, $\mathsf{tick} = \mathsf{tick}'$ and $\mathsf{blame} = \mathsf{blame}'$. In other words, a state region of this expanded state space is a set of the form $\{\ell\} \times R \times \{\mathsf{tick}\} \times \{\mathsf{blame}\}$ where $\ell \in L$, $R \in \mathsf{Reg}$, $\mathsf{tick}, \mathsf{blame} \in \{\mathsf{true}, \mathsf{false}\}$, i.e., obtained by taking a state region and adding two fixed Boolean values for the last components.

We can define time-divergence and blamelessness as ω-regular conditions using the two additional Boolean values. A play of the expanded game is time-divergent if and only if infinitely many states of the form $(s, \mathsf{true}, \mathsf{blame})$ appear along it (i.e., the global clock passes infinitely many integer bounds along the play). A play is blameless if and only if from some

index on, only states of the form $(s, \mathsf{tick}, \mathsf{false})$ are visited, i.e., if from some point on, $\mathcal{P}_1$ is no longer responsible for transitions.

Parity automata for winning conditions.   We consider ω-regular objectives specified by deterministic parity automata. We explain how to derive a DPA encoding the winning condition using the additional information of $\widehat{\mathcal{G}}$ from a DPA specifying a region objective in the TG $\mathcal{G}$.

Let us fix a DPA $H = (Q, q_{\mathsf{init}}, L \times \mathsf{Reg}, \mathsf{up}, p)$. One can derive from H a DPA $\widehat{H}$ encoding the winning condition $\mathsf{WC}_1(\mathcal{L}(H))$ in the expanded game $\widehat{\mathcal{G}}$. Formally, we define $\widehat{H} = (\widehat{Q}, \widehat{q}_{\mathsf{init}}, (L \times \mathsf{Reg}) \times \{\mathsf{true}, \mathsf{false}\}^2, \widehat{\mathsf{up}}, \widehat{p})$, where $\widehat{Q} = Q \times \{\mathsf{true}, \mathsf{false}\}^2 \times \{0, \ldots, \mathsf{D} - 1\}$, $\widehat{q}_{\mathsf{init}} = (q_{\mathsf{init}}, \mathsf{false}, \mathsf{false}, d)$, for any $\widehat{q} = (q, \mathsf{tick}, \mathsf{blame}, h) \in \widehat{Q}$ and $\widehat{s} = ([s], \mathsf{tick}', \mathsf{blame}')$, we have

$$\widehat{\mathsf{up}}(\widehat{q}, \widehat{s}) = \begin{cases} (q', \mathsf{tick}', \mathsf{blame}', p(q')) & \text{if } \mathsf{tick} = \mathsf{true} \\ (q', \mathsf{tick}', \mathsf{blame}', \min\{h, p(q')\}) & \text{otherwise,} \end{cases}$$

where $q' = \mathsf{up}(q, [s])$, and

$$\widehat{p}(\widehat{q}, \widehat{s}) = \begin{cases} h & \text{if } \mathsf{tick} = \mathsf{true} \\ \mathsf{D}' & \text{if } \mathsf{tick} = \mathsf{false} \text{ and } \mathsf{blame} = \mathsf{true}, \\ \mathsf{D}' + 1 & \text{otherwise} \end{cases}$$

where $\mathsf{D}' = \mathsf{D}$ if D is odd, and otherwise $\mathsf{D}' = \mathsf{D} - 1$. The DPA $\widehat{H}$ encodes an objective of $\widehat{\mathcal{G}}$ in the same way that H encodes an objective of $\mathcal{G}$. This objective is the winning condition for the following reasons.

The rough idea of the construction is to keep track of the smallest priority in H seen between two ticks and output it whenever tick holds. This way, whenever tick holds infinitely often, the smallest priority appearing in an execution of $\widehat{H}$ is the same as the smallest priority in the matching execution of H, because we chose D' greater or equal to all of the priorities of H.

If tick holds finitely often however (i.e., we consider a time-convergent play), from some point on only the priorities D' and $\mathsf{D}' + 1$ are seen. We see the smaller odd priority D' whenever $\mathcal{P}_1$ is responsible for a transition; it follows that, in this case, we have a rejecting execution of $\widehat{H}$ if and only if $\mathcal{P}_1$ is not blameless.

For the remainder of this section, we fix a DPA $H = (Q, q_{\mathsf{init}}, L \times \mathsf{Reg}, \mathsf{up}, p)$ and let $\widehat{H}$ denote its adaptation as defined above.

Computing the set of winning states.   We explain how to compute the set of winning states of $\widehat{\mathcal{G}}$. The idea is to solve an infinite parity game obtained via the synchronous product of the expanded game $\widehat{\mathcal{G}}$ with the expanded DPA $\widehat{H}$. This approach is presented in [24] and underlies the algorithmic solution of [23].

The synchronous product of $\widehat{\mathcal{G}}$ and $\widehat{H}$, which we will denote by $\widehat{\mathcal{G}} \times \widehat{H}$, is obtained in the usual way. At each step of the TG $\widehat{\mathcal{G}}$, we feed the state region, tick and blame components of the current state to the DPA $\widehat{H}$. In the sequel, because the tick and blame components in both $\widehat{\mathcal{G}}$ and $\widehat{H}$ coincide (by nature of the product), we omit one of the two in the upcoming definitions.

Formally, we obtain a game played on the state space $S \times \widehat{Q}$, with the joint destination function $\widehat{\mathsf{JD}}_\times : S \times \widehat{Q} \times M_1 \times M_2 \to 2^{S \times \widehat{Q}}$ defined by, for all $(s, \widehat{q}) \in S \times \widehat{Q}$, $\widehat{q} = (q, \mathsf{tick}, \mathsf{blame}, h)$,

and all $m^{(1)} \in M_1(s)$ and $m^{(2)} \in M_2(s)$,

$$\widehat{\mathsf{JD}}_\times((s, \widehat{q}), m^{(1)}, m^{(2)}) = \{(s', \widehat{q}') \mid \widehat{s}' = (s', \mathsf{tick}', \mathsf{blame}') \in \widehat{\mathsf{JD}}(\widehat{s}, m_1, m_2) \wedge \widehat{q}' = \widehat{\mathsf{up}}(\widehat{q}, [\widehat{s}'])\},$$

where $\widehat{s} = (s, \mathsf{tick}, \mathsf{blame})$.

On this product game, the objective of $\mathcal{P}_1$ is a parity objective. The priority function $\widehat{p}_\times$ from which this objective is defined assigns to each state $(\widehat{s}, q, h)$ the priority $\widehat{p}(\widehat{q})$.

Winning in the product game $\widehat{\mathcal{G}} \times \widehat{H}$ and winning in the original TG $\mathcal{G}$ are related as follows. There is a winning strategy for $\mathcal{P}_1$ in a state $s \in S$ in $\mathcal{G}$ for the (winning condition induced by the) objective encoded by H if and only if there is a winning strategy for $\mathcal{P}_1$ from the state $(s, \mathsf{up}(q_{\mathsf{init}}, [s]), \mathsf{false}, \mathsf{false}, d-1)$ in $\widehat{\mathcal{G}} \times \widehat{H}$ for the parity objective given by $\widehat{p}_\times$. This can be established by showing that from any winning strategy in the product game, one can derive a winning strategy in the original TG and vice-versa.

The set of winning states in the product game can be computed by a linear-size μ-calculus formula of alternation depth $\mathsf{D}' + 2 \leq \mathsf{D} + 2$ [24]. Furthermore, and all sets involved in its computation are unions of state regions [23], i.e., its evaluation can be performed on the finite region abstraction (albeit of the product game). The following result follows.

▶ **Theorem 1.** *The set of winning states of $\mathcal{P}_1$ in the TG $\mathcal{G}$ for the objective given by H is a union of state regions and is computable in time $\mathcal{O}((4 \cdot |L| \cdot |\mathsf{Reg}| \cdot |Q| \cdot \mathsf{D})^{\mathsf{D}'+2})$.*

Let us now discuss winning strategies in the product game. A strategy is said to be *memoryless* if for any two histories ending in the same state, the same move is prescribed. In parity games, memoryless strategies suffice for winning (e.g., [26, 38]). In the product game $\widehat{\mathcal{G}} \times \widehat{H}$, one can find winning memoryless strategies that are well-behaved with respect to regions. A memoryless strategy $\sigma \colon S \times \widehat{Q} \to M_1$ is said to be a *memoryless region strategy* if for any two states $(s_1, \widehat{q}), (s_2, \widehat{q}) \in S \times \widehat{Q}$, where $s_1 = (\ell_1, v_1)$ and $s_2 = (\ell_2, v_2)$, if $s_1 \equiv_{\mathcal{A}} s_2$, then the moves $(\delta_1, a_1) = \sigma((s_1, \widehat{q}))$ and $(\delta_2, a_2) = \sigma((s_2, \widehat{q}))$ are such that $a_1 = a_2$, $[v_1 + \delta_1] = [v_2 + \delta_2]$ and $\{[v_1 + \delta_{\mathsf{mid}}] \mid 0 \leq \delta_{\mathsf{mid}} \leq \delta_1\} = \{[v_2 + \delta_{\mathsf{mid}}] \mid 0 \leq \delta_{\mathsf{mid}} \leq \delta_2\}$. Such memoryless region strategies suffice for winning in $\widehat{\mathcal{G}} \times \widehat{H}$.

A function $f \colon (L \times \mathsf{Reg}) \times \widehat{Q} \to U$, where U denotes the set of unions of elements of $(L \times \mathsf{Reg}) \times \widehat{Q}$, can be derived during the evaluation of the μ-calculus formula mentioned above. This function f describes a memoryless winning strategy at the region level [24, 23]; a memoryless winning strategy is obtained by assigning to any winning state $(s, \widehat{q}) \in S \times \widehat{Q}$ some move $m^{(1)}$ such that for any move $m^{(2)}$ of $\mathcal{P}_2$ enabled in $(s, \widehat{q})$, we have $\mathsf{JD}_\times((s, \widehat{q}), m^{(1)}, m^{(2)}) \subseteq f(([s], \widehat{q}))$ – such a move is guaranteed to exist assuming that $\mathcal{P}_1$ has a winning strategy from $(s, \widehat{q})$.

We explain how a memoryless winning region strategy can be obtained from f. The choice of moves only matters in regions from which $\mathcal{P}_1$ wins. Fix a state $(s, \widehat{q}) \in S \times \widehat{Q}$ with $s = (\ell, v)$ and let $m = (\delta, a)$ be any move that could have been assigned in $(s, \widehat{q})$ by a winning strategy derived from f. Let $s' = (\ell', v') \in S$ such that $s' \equiv_{\mathcal{A}} s$; we argue that we can find a move $m' = (\delta', a)$ such that $[v + \delta] = [v' + \delta']$, $\{[v + \delta_{\mathsf{mid}}] \mid 0 \leq \delta_{\mathsf{mid}} \leq \delta\} = \{[v' + \delta_{\mathsf{mid}}] \mid 0 \leq \delta_{\mathsf{mid}} \leq \delta'\}$ and for any move $m^{(2)}$ of $\mathcal{P}_2$ enabled in $(s', \widehat{q})$, we have $\mathsf{JD}_\times((s', \widehat{q}), m', m^{(2)}) \subseteq f(([s'], \widehat{q}))$. The properties of clock regions ensures that there exists some δ' satisfying the first two conditions. Fix any such δ'. The third condition follows from the facts that (i) $s \equiv_{\mathcal{A}} s'$ implies $f(([s], \widehat{q})) = f(([s'], \widehat{q}))$ and (ii) m and m' traverse and reach the same regions, therefore if $\mathcal{P}_2$ has a move (δ_2', b) enabled in s' with $\delta_2' \leq \delta'$, then there is some $\delta_2 \leq \delta$ such that $[v + \delta_2] = [v' + \delta_2']$, therefore the sets of regions $\{[s''] \mid (s'', \widehat{q}') \in \mathsf{JD}_\times((s, \widehat{q}), m, (\delta_2, b))\}$ and $\{[s''] \mid (s'', \widehat{q}') \in \mathsf{JD}_\times((s', \widehat{q}), m', (\delta_2', b))\}$ are the same, which implies the third condition in conjunction with (i).

Simplifying the structure of winning strategies.   In the previous section, we have explained that in the product parity game $\widehat{\mathcal{G}} \times \widehat{H}$, memoryless region strategies suffice and are computable. To replicate the behavior of these strategies in the original TG $\mathcal{G}$, one needs to observe the moves of the players, e.g., to keep track of the blame component. The goal of this section is to show that we can simplify winning strategies in two regards, with the goal of deriving finite-memory strategies that do not take in account the moves of the players.

Let us fix a memoryless winning region strategy $\sigma\colon S \times \widehat{Q} \to M_1$ of $\mathcal{P}_1$ in the product game. First, we show that the blame component is irrelevant to the decision of the strategy. Formally, we show that we can select a winning strategy such that if two expanded states $(s, \widehat{q}_1)$ and $(s, \widehat{q}_1)$ differ only in their blame Boolean value, then the strategy prescribes the same move in both states. Second, we show that we can bound the delays proposed by a winning strategy, in such a way that whether tick holds or not can be inferred without examining the delays in the moves.

To show that the blame Boolean can be disregarded, we provide a non-constructive argument. The essence of the argument is that one can find a winning strategy which assigns the same move to two states that possess the same successors.

▶ **Lemma 25.** *In the game $\widehat{\mathcal{G}} \times \widehat{H}$, region memoryless strategies that disregard the blame Boolean suffice for winning.*

Proof. In (potentially infinite) turn-based parity games, memoryless strategies that select the same action in two states with the same successors suffice for winning; this follows from the proof of Emerson and Jutla [26] that memoryless strategies suffice in turn-based parity games with finitely many priorities.

While the game $\widehat{\mathcal{G}} \times \widehat{H}$ is not turn-based, the definition of winning we use (i.e., winning no matter the strategy of $\mathcal{P}_2$) allows us to apply the previous result. Indeed, winning in the concurrent product game $\widehat{\mathcal{G}} \times \widehat{H}$ is trivially equivalent to winning in a turn-based game in which first $\mathcal{P}_1$ selects a move, and then $\mathcal{P}_2$ is informed of $\mathcal{P}_1$'s move and has the choice to preempt $\mathcal{P}_1$ or to let $\mathcal{P}_1$'s move induce the next transition.

In light of the above and the fact that two states that differ only from their blame component possess the same successors, this ends the proof.   ◀

While the argument above is non-constructive, memoryless winning region strategies are constructed in practice using algorithms for finite parity games [24]. One can show that winning strategies constructed by Zielonka's recursive algorithm [38] can be built such that two successor-sharing states are assigned the same action. This is due to the fact that the building blocks of these winning strategies are so-called attractor strategies, and intuitively that successor-sharing states are in the same attractor sets when neither are target states.

We now move on to the second step in our simplification of winning strategies. The goal of the upcoming construction is to have ticks be detectable by observing only the current state region and using one bit of information. The role of the bit of information is to remember whether the valuation of the global clock was integral or not at the previous step. This allows us to infer that tick holds in some cases: tick holds whenever the valuation of the global clock is integral at the current step but was not at the previous step.

In the sequel, we show that the delays proposed by a strategy can be constrained in such a way that all ticks are detectable by the mechanism described above. Intuitively, our construction consists, given a memoryless winning strategy that disregards the blame Boolean, to replace proposed moves that have a large delay by delay moves with small delays in such a way that the strategy obtained this way is still winning, and that all ticks are observable.

It remains to clarify what we mean by a large delay. On the one hand, any delay such that the global clock passes an integer bound strictly is considered large; we cannot observe that the global clock was integral at some point in time during the transition in this case. On the other hand, a delay of one is also considered large: from regions, we can only observe whether the valuation of the global clock is integral or not. If we move between two states in which the valuation of the global clock is integral, it cannot be known without observing the moves whether the transition was taken with a non-zero delay or not, therefore ticks cannot be observed.

We formally state and prove the announced result hereunder. Let us underline that in the following proof, to lighten notation, we denote by $\widehat{s}$ states of the product game $\widehat{\mathcal{G}} \times \widehat{H}$. In previous sections, we had used such a notation for states of the expanded game $\widehat{\mathcal{G}}$.

▶ **Lemma 26.** *In the game $\widehat{\mathcal{G}} \times \widehat{H}$, region memoryless strategies σ that satisfy the following constraints suffice for winning: σ disregards the blame Boolean and for any state $\widehat{s} = ((\ell, v), \widehat{q}) \in S \times \widehat{Q}$, we have $\mathsf{delay}(\sigma(\widehat{s})) \leq 1 - \mathsf{frac}(v(\gamma))$, and this inequality is strict whenever $v(\gamma) \in \mathbb{N}$.*

Proof. Let $\widehat{s}_{\mathsf{init}} \in S \times \widehat{Q}$ be a state from which $\mathcal{P}_1$ wins. Let σ denote a memoryless region strategy winning from $\widehat{s}_{\mathsf{init}}$ that disregards the blame Boolean, the existence of which is ensured by Lemma 25. We explicitly derive a suitable strategy $\widetilde{\sigma}$ from σ and show it is winning.

For any state $\widehat{s} = ((\ell, v), \widehat{q}) \in S \times \widehat{Q}$, we let $f = \mathsf{frac}(v(\gamma))$ and define

$$\widetilde{\sigma}(\widehat{s}) = \begin{cases} \sigma(\widehat{s}) & \text{if } \mathsf{delay}(\sigma(\widehat{s})) \leq 1 - f \text{ and } v(\gamma) \notin \mathbb{N} \\ (1 - f, \bot) & \text{if } \mathsf{delay}(\sigma(\widehat{s})) > 1 - f \text{ and } v(\gamma) \notin \mathbb{N} \\ \sigma(\widehat{s}) & \text{if } \mathsf{delay}(\sigma(\widehat{s})) < 1 - f \text{ and } v(\gamma) \in \mathbb{N} \\ (\frac{1}{2}(1 - \max_{x \in C} \mathsf{frac}(v(x))), \bot) & \text{if } \mathsf{delay}(\sigma(\widehat{s})) \geq 1 - f \text{ and } v(\gamma) \in \mathbb{N}. \end{cases}$$

This memoryless strategy $\widetilde{\sigma}$ disregards the blame Boolean because σ does, and satisfies the delay-related constraints by construction. To end the proof, we must show that $\widetilde{\sigma}$ is a region strategy and that it is winning.

First, let us show that it is a memoryless region strategy. Let $\widehat{s}_1$ and $\widehat{s}_2$ be two region-equivalent states. Because σ is a region strategy, it proposes moves in both $\widehat{s}_1$ and $\widehat{s}_2$ that traverse and reach the same region. In particular, given that ticks are encoded in states in the product game $\widehat{\mathcal{G}} \times \widehat{H}$, and that cases in the definition of $\widetilde{\sigma}$ depend on whether tick holds or not after the move proposed by σ, it follows that both $\widehat{s}_1$ and $\widehat{s}_2$ fall into the same case.

In the first or third cases, $\widetilde{\sigma}$ proposes the same move as σ, therefore there is nothing to show. We restrict for the remainder of this paragraph our attention to the set of clocks containing the global clock and the clocks such that their valuation in $\widehat{s}_1$ (or equivalently in $\widehat{s}_2$) has not yet exceeded the largest constant to which they are compared to in $\mathcal{A}$. Clocks for which the valuation has exceeded this threshold need not be taken in account to prove that the delays $\widetilde{\sigma}$ proposes traverse and reach the same regions from both $\widehat{s}_1$ and $\widehat{s}_2$ (by definition of regions).

In the second and fourth cases, $\widetilde{\sigma}$ prescribes a delay move; it does not affect the ordering of the fractional parts of the valuations of the clocks. It follows that we need only check that the same clocks have pass and reach an integral value during and after the delay prescribed by $\widetilde{\sigma}$ in $\widehat{s}_1$ and $\widehat{s}_2$ respectively. In the second case of the definition of $\widetilde{\sigma}$, the only clocks that have an integral valuation after the delay are those with the same fractional part in their valuation as γ by choice of the delay. Furthermore, the valuation of any clock that had a

fractional part greater than that of γ before the delay passes an integer bound during the delay. In the fourth case, the chosen delay is such that the valuation of no clock passes an integer bound after the delay. This shows that in both cases, the same regions are traversed and reached from both states. This concludes the proof that $\widetilde{\sigma}$ is a region strategy.

It remains to show that $\widetilde{\sigma}$ is winning to end the proof. The idea for the remainder of this proof is to show that for any outcome $\widetilde{\pi}$ of $\widetilde{\sigma}$ from $\widehat{s}_{\mathsf{init}}$, one can find an analogous outcome π from $\widehat{s}_{\mathsf{init}}$ of σ (by changing the moves of $\mathcal{P}_2$) and use the fact that π is winning to show that $\widetilde{\pi}$ is also winning.

Let $\widetilde{\pi} = \widetilde{s}_0(\widetilde{m}_0^{(1)}, \widetilde{m}_0^{(2)})\widetilde{s}_2 \ldots$ be an outcome of $\widetilde{\sigma}$. We consider the outcome $\pi = \widehat{s}_0(m_0^{(1)}, m_0^{(2)})\widehat{s}_2 \ldots$ of σ where $\widehat{s}_0 = \widetilde{s}_0$, and for all $k \in \mathbb{N}$, $m_k^{(1)} = \sigma(\widehat{s}_k)$ and, if $m_k^{(1)} = \widetilde{m}_k^{(1)}$ or $\mathcal{P}_2$ is responsible for the transition at step k in $\widetilde{\pi}$, we let $m_k^{(2)} = \widetilde{m}_k^{(2)}$ and $\widehat{s}_{k+1} = \widetilde{s}_{k+1}$, and otherwise, we let $m_k^{(2)} = \widetilde{m}_k^{(1)}$ (i.e., $\mathcal{P}_2$ takes over the delay move of $\mathcal{P}_1$) and $\widehat{s}_{k+1}$ is obtained by reversing the blame Boolean of $\widetilde{s}_{k+1}$. We note that the play π is a well-defined play because by construction, $\widetilde{\sigma}$ proposes shorter delays than σ. Since we assume that σ is winning, it follows that π satisfies the parity objective.

It now remains to show that $\widetilde{\pi}$ is winning for the parity objective. Assume first that tick holds infinitely often in $\widetilde{\pi}$. It follows by construction that tick holds infinitely often in π. In this case, the structure of the priority function of the product game $\widehat{\mathcal{G}} \times \widehat{H}$ ensures that the smallest priority occurring infinitely often in $\widetilde{\pi}$ and π coincide, i.e., $\widetilde{\pi}$ is winning for the parity objective.

Let us now assume that tick holds only finitely often in $\widetilde{\pi}$ and therefore in π. Because π is winning, it follows that there exists an index $n \in \mathbb{N}$ such that for all $k \geq n$, both the tick and blame components of $\widehat{s}_k$ evaluate to false. By construction of π, for all $k \geq n$, the tick component of $\widetilde{s}_k$ evaluates to false. In the remainder of the proof, we argue that there is at most one $k \geq n$, such that the blame component of $\widetilde{s}_k$ is true.

Let us fix $k \geq n$. If $\widetilde{m}_{k-1}^{(1)} = m_{k-1}^{(1)}$, we have $\widetilde{s}_k = \widehat{s}_k$, hence the blame component of $\widetilde{s}_k$ evaluates to false. Let us assume instead that $\widetilde{m}_{k-1}^{(1)} \neq m_{k-1}^{(1)}$. There are two possibilities: either the valuation of γ in $\widetilde{s}_{k-1}$ is not an integer or it is an integer. The former case is easiest to handle: by definition of $\widetilde{\sigma}$, because the move is changed, it means that the move $m_{k-1}^{(1)}$ has a delay large enough that tick would hold after using it, therefore the move $\widetilde{m}_{k-1}^{(1)}$ is defined in such a way that tick would hold after using it. However, because tick does not hold in $\widetilde{s}_k$, it follows that blame does not hold either. Now, let us place ourselves in the latter case and assume that the valuation of γ is integral in $\widetilde{s}_{k-1}$. In this case $\widetilde{\sigma}$ proposes a delay move with a strictly positive delay. In these circumstances, it may be the case that $\mathcal{P}_1$ is responsible for the transition, but this can happen at most once: after one such transition, the valuation of the global clock is never an integer again as there are no more ticks. This shows that $\widetilde{\pi}$ is winning in this second case. This concludes the proof that the strategy $\widetilde{\sigma}$ is winning, and with this, the entire proof. ◀

Finite-memory strategies. Up to now, we have been concerned with winning strategies in the expanded game structure. In this section, we describe how to derive winning finite-memory region strategies from the memoryless winning region strategies on the product $\widehat{\mathcal{G}} \times \widehat{H}$. The role of the Mealy machine is to keep track of the additional information contained in the expanded product game.

It follows from Lemma 26 that to win in the expanded product game, one can disregard the blame Boolean and restrict themselves to delays that prevent the occurrence of two ticks in a row. Let us fix one such winning memoryless region strategy $\sigma \colon S \times \widehat{Q} \to M_1$ for the remainder of this section.

The structure of the Mealy machine encoding the finite-memory strategy we derive from σ is very close in nature to the structure of $\widehat{H}$. The main difference is that neither ticks nor blame are observable from state regions in the TG $\mathcal{G}$, which is why we simplified strategies to overcome these limitations.

We provide the construction of the Mealy machine in the proof of the following formal statement.

▶ **Theorem 2.** *There exists a finite-memory region strategy with $2 \cdot |Q| \cdot \mathsf{D}$ states proposing delays of at most 1 that is winning for the objective specified by H from any state that is winning for $\mathcal{P}_1$.*

Proof. It suffices to show that using a finite-memory strategy, it is possible to emulate σ in $\mathcal{G}$. Any strategy constructed this way is winning due to the relations between the games $\mathcal{G}$ and $\widehat{\mathcal{G}} \times \widehat{H}$. The state space of the upcoming Mealy machine is a essentially a simplification of $\widehat{Q}$: states are of the form (int, q, h) where $\mathsf{int} \in \{\mathsf{true}, \mathsf{false}\}$ holds if and only if the valuation of the global clock was integral at the previous step, $q \in Q$ is some state of H and $h \in \{0, \ldots, \mathsf{D}-1\}$ is the smallest priority seen since the last tick. We also use $h = \mathsf{D}-1$ in case no priorities were seen, i.e., if a tick has occurred in the current step.

We formally define the Mealy machine $\mathcal{M} = (\mathfrak{M}, \mathfrak{m}_{\mathsf{init}}, \alpha_{\mathsf{up}}, \alpha_{\mathsf{mov}})$ as follows. The state space is $\mathfrak{M} = \{\mathsf{true}, \mathsf{false}\} \times Q \times \{0, \ldots, \mathsf{D}-1\}$ and the initial state is $\mathfrak{m}_{\mathsf{init}} = (\mathsf{true}, q_{\mathsf{init}}, p(q_{\mathsf{init}}))$. Prior to defining the update function $\alpha_{\mathsf{up}} \colon \mathfrak{M} \times (L \times \mathsf{Reg}) \to \mathfrak{M}$ and next-move function $\alpha_{\mathsf{mov}} \colon \mathfrak{M} \times S \to M_1$, we introduce some notation. Let $\mathfrak{m} = (\mathsf{int}, q, h) \in \mathfrak{M}$ and $s = (\ell, v) \in S$. We denote by $q' = \mathsf{up}(q, [(\ell, v)])$ the successor of q in H after reading $[s]$. We also let int' hold if and only if $v(\gamma) \in \mathbb{N}$. The definition of $\alpha_{\mathsf{up}}(\mathfrak{m}, [s])$ is:

$$\alpha_{\mathsf{up}}(\mathfrak{m}, [s]) = \begin{cases} (\mathsf{int}', q', \mathsf{D}-1) & \text{if } \neg\mathsf{int} \text{ and } \mathsf{int}' \text{ hold} \\ (\mathsf{int}', q', \min\{p(q'), h\}) & \text{otherwise} \end{cases}$$

and the definition of $\alpha_{\mathsf{mov}}(\mathfrak{m}, s)$ is:

$$\alpha_{\mathsf{mov}}(\mathfrak{m}, s) = \begin{cases} \sigma(s, q', \mathsf{true}, \mathsf{false}, \min\{h, p(q')\}) & \text{if } \neg\mathsf{int} \text{ and } \mathsf{int}' \text{ hold} \\ \sigma(s, q', \mathsf{false}, \mathsf{false}, \min\{h, p(q')\}) & \text{otherwise.} \end{cases}$$

The Mealy machine that $\mathfrak{M}$ encodes a finite-memory region strategy because σ is a region strategy. We now briefly explain why $\mathcal{M}$ encodes a strategy in $\mathcal{G}$ with the same behavior as σ. This implies that the encoded strategy is winning.

In the product game $\widehat{\mathcal{G}} \times \widehat{H}$, updates of the DPA component are performed using the state we move into. Given that this is not possible in practice (we do not know in advance where we will be at the next step), the Mealy machine is always one step behind. This explains why in the evaluation of σ used in the definition of α_{mov}, we use q' rather than q and the priority of q' in the last argument of the function. By choice of σ, two ticks cannot occur consecutively, therefore at some step, tick holds if and only if int did not hold previously and holds now. This justifies the two distinguished cases in the definitions of both α_{up} and α_{mov}.

Finally, it remains to explain that the priority fed to σ (i.e., last component in the evaluation of σ) is well-chosen. Whenever a tick is registered by $\widehat{H}$, the last component is reset to the priority of the successor state in the execution of H following the current history. In our case, we cannot guess what will be this priority will be in advance. Instead, we set $\mathsf{D}-1$ as the current lowest priority after a tick. This way, this greatest priority is disregarded by the min operator in the definition of α_{mov}.

◀

▶ Remark 27. The assumption of a global clock γ is crucial for the existence of finite-memory winning strategies. In fact, if one removes this global clock, winning may require infinite memory and observing the moves [21]. Essentially, this infinite memory can be described as a simulation of the clock γ.