Partial Order Reduction for Reachability Games

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Abstract
Partial order reductions have been successfully applied to model checking of concurrent systems and practical applications of the technique show nontrivial reduction in the size of the explored state space. We present a theory of partial order reduction based on stubborn sets in the game-theoretical setting of 2-player games with reachability/safety objectives. Our stubborn reduction allows us to prune the interleaving behaviour of both players in the game, and we formally prove its correctness on the class of games played on general labelled transition systems. We then instantiate the framework to the class of weighted Petri net games with inhibitor arcs and provide its efficient implementation in the model checker TAPAAL. Finally, we evaluate our stubborn reduction on several case studies and demonstrate its efficiency.

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Petri nets, games, synthesis, partial order reduction, stubborn sets

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1 Introduction
The state space explosion problem is the main obstacle for model checking of concurrent systems as even very simple processes running in parallel can produce an exponentially large number of possible interleavings and hence make the state space search practically intractable. One of the ways to tame this problem is by employing a variety of partial order reduction techniques, including the seminal work on stubborn set reductions by Valmari et al. [24, 23, 25].

As our main contribution, we generalize the theory of partial order reductions into the framework of 2-player games. The idea is that whenever one of the players can perform a series of moves in different sub-components of the system in parallel (without being disturbed by the other player), we may apply the classical stubborn set reductions in order to reduce the number of interleavings of independent actions. There is a number of subtree points that...
one has to satisfy so that the reduced game preserves the winning strategies of both players. We formulate a number of sufficient conditions that define the notion of a stable stubborn set reduction that guarantees the preservation of winning strategies for both players in the game. In the setting of general game labelled transition systems, we formally prove the correctness of stable reductions and we demonstrate the applicability of the framework on weighted Petri net games with inhibitor arcs. We show how to approximate in a syntax-driven manner the conditions of a stable Petri net game reduction and provide an efficient, open source implementation in the model checker TAPAAL [6]. We also implement a game engine based on dependency graphs, following the approach from [14, 5], and on several case studies evaluate the game engine both with and without the use of the stable stubborn set reduction. The experiments demonstrate that the computation of the stubborn sets has only a minor overhead and has the potential of achieving exponential reduction both in the running time as well as in the number of searched configurations. We believe that this is the first implementation of 2-player game partial order reduction technique for Petri nets working in practice.

**Related Work.** Partial order reductions in the non-game setting for linear time properties have previously been studied [19, 23, 18, 17] which lends itself towards the safeness or liveness properties we want to preserve for winning states. In [19] and [23] Peled and Valmari present partial order reductions for general LTL. In [18] Lehmann et al. study stubborn sets applied to a subset of LTL properties called simple linear time properties which does not require all the requirements for general LTL preservation.

The extension of partial order reductions to game-oriented formalisms and verification tasks has not yet received much attention in the literature. In [10] partial order reductions for LTL without the next operator are adapted to a subset of alternating-time temporal logic and applied to multi-agent systems. The authors considers games with imperfect information, however they also show that their technique does not work for strategies with perfect information. We assume an antagonistic environment and focus on preserving the existence of winning strategies with perfect information, reducing the state space and improving existing controller synthesis algorithms. Partial order reduction for the problem of checking bisimulation equivalence between two labelled transition systems is presented in [9]. Our partial order reduction is applied directly to a labelled transition system while theirs are applied to the bisimulation game graph. While the setting is distinctly different, our approach is more general as we allow for mixed states, provide less information to the controller, and allow for reduction in both controllable as well as environmental states. Moreover, we provide an implementation of the on-the-fly strategy synthesis algorithm and argue by a number of case studies for its practical applicability.

The work on partial order reductions for modal mu-calculus and CTL (see e.g. [21, 26]) allows us in principle to encode the game semantics as a part of the mu-calculus formula, however, there is to the best of our knowledge no literature documenting the practical applicability of this approach.

Complexity and decidability results for control synthesis in Petri nets games are not encouraging. The control synthesis problem is for many instances of Petri net formalisms undecidable [1, 2], including those that allow for inhibition [2] which we utilise to model our case studies. If the problem is decidable for a given instance of a Petri net formalism (like e.g. for bounded nets) then it is usually of exponential complexity. In fact, most questions about the behaviour of bounded Petri nets are at least PSPACE-hard [11]. Among these questions is the existence of an infinite run [7] that we need to test as one of the sufficient
conditions for applying stubborn set reductions to games. Instead of using exact infinite run detection approaches like in [7], we opt for efficient overapproximation algorithms to detect cycles using both syntactic and local state information.

2 Preliminaries

Definition 1 (Game Labelled Transition System). A (deterministic) Game Labelled Transition System (GLTS) is a tuple $G = (S, A_1, A_2, \rightarrow, \text{Goal})$ where $S$ is a set of states, $A_1$ is a finite set of actions for player 1 (the controller), $A_2$ is a finite set of actions for player 2 (the environment) where $A_1 \cap A_2 = \emptyset$ and $A = A_1 \cup A_2, \rightarrow \subseteq S \times A \times S$ is a transition relation s.t. if $(s, a, s') \in \rightarrow$ and $(s, a, s'') \in \rightarrow$ then $s' = s''$, and Goal $\subseteq S$ is a set of goal states.

Let $G = (S, A_1, A_2, \rightarrow, \text{Goal})$ be a fixed GLTS for the remainder of the section. Whenever $(s, a, s') \in \rightarrow$ we write $s \xrightarrow{a} s'$ and say that $a$ is enabled in $s$ and can be fired in $s$ yielding $s'$. Otherwise we say that $a$ is disabled in $s$. The set of enabled player $i$ actions where $i \in \{1, 2\}$ in a state $s \in S$ is given by $en_i(s) = \{a \in A_i \mid \exists s' \in S, s \xrightarrow{a} s'\}$. The set of all enabled actions is given by $en(s) = en_1(s) \cup en_2(s)$. For a state $s \in S$ where $en(s) \neq \emptyset$ if $en_2(s) = \emptyset$ then we call $s$ a player 1 state, if $en_1(s) = \emptyset$ then we call $s$ a player 2 state, and otherwise we call it a mixed state. The GLTS $G$ is called non-mixed if all states are either player 1 or player 2 states. For a sequence of actions $w = a_1 a_2 \cdots a_n \in A^*$ we write $s \xrightarrow{w} s'$ if $s \xrightarrow{a_1} s_1 \xrightarrow{a_2} \cdots \xrightarrow{a_n} s'$. If $w \in A^\omega$, i.e. it is infinite, then we write $s \xrightarrow{\omega}$. Actions that are a part of $w$ are said to occur in $w$. A sequence of states induced by $w \in A^* \cup A^\omega$ is called a run and is written as $\pi = s_0 s_1 \cdots$. We use $\Pi_G(s)$ to denote the set of all runs starting from a state $s \in S$ in GLTS $G$, s.t. for all $s_0 s_1 \cdots \in \Pi_G(s)$ we have $s_0 = s$, and $\Pi_G = \bigcup_{s \in S} \Pi_G(s)$ as the set of all runs. The length of a run $\pi$ (number of states in the run) is given by the function $\ell : \Pi_G \rightarrow \mathbb{N}^0 \cup \{\infty\}$. A position in a run $\pi = s_0 s_1 \cdots \in \Pi_G(s)$ is a natural number $i \in \mathbb{N}^0$ that refers to the state $s_i$, and is written as $\pi_i$. A position $i$ can range from 0 to $\ell(\pi)$ s.t. if $\pi$ is infinite then $i \in \mathbb{N}^0$ and otherwise $0 \leq i \leq \ell(\pi)$. Let $\Pi_G^{\text{max}}(s)$ be the set of all maximal runs starting from $s$, defined as $\Pi_G^{\text{max}}(s) = \{\pi \in \Pi_G(s) \mid \ell(\pi) = \infty \lor en(\pi_i(s_1)) = \emptyset\}$. We omit the GLTS $G$ from the subscript of run sets if it is clear from the context.

A reduced game is defined by a function called a reduction.

Definition 2 (Reduction). Let $G = (S, A_1, A_2, \rightarrow, \text{Goal})$ be a GLTS. A reduction is a function $St : S \rightarrow 2^A$.

Definition 3 (Reduced Game). Let $G = (S, A_1, A_2, \rightarrow, \text{Goal})$ be a GLTS and $St$ be a reduction. The reduced game of $G$ by the reduction $St$ is given by $G_{St} = (S, A_1, A_2, \rightarrow_{St}, \text{Goal})$ where $s \xrightarrow{a}_{St} s'$ iff $s \xrightarrow{a} s'$ and $a \in St(s)$.

The set of actions $St(s)$ is the stubborn set of $s$ with the reduction $St$. The set of non-stubborn actions for $s$ is defined as $\overline{St}(s) = A \setminus St(s)$.

A (memoryless) strategy is a function which proposes the next action player 1 wants to be fired.

Definition 4 (Strategy). Let $G = (S, A_1, A_2, \rightarrow, \text{Goal})$ be a GLTS. A strategy is a function $\sigma : S \rightarrow A_1 \cup \{\bot\}$ where for all $s \in S$ we have if $en_1(s) \neq \emptyset$ then $\sigma(s) \in en_1(s)$ else $\sigma(s) = \bot$. 

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The intuition is that in order to ensure progress, player 1 always has to propose an action if she has an enabled action. Let \(\sigma\) be a fixed strategy for the remainder of the section. We define a function \(\text{next}_\sigma(s)\) that returns the set of actions considered at \(s \in S\) under \(\sigma\) as:

\[
\text{next}_\sigma(s) = \begin{cases} 
  e_{n_2}(s) \cup \sigma(s) & \text{if } \sigma(s) \neq \perp \\
  e_{n_2}(s) & \text{otherwise.}
\end{cases}
\]

Let \(\Pi^\text{max}_\sigma(s) \subseteq \Pi^\text{max}(s)\) be the set of maximal runs subject to \(\sigma\) starting at \(s \in S\), defined as:

\[
\Pi^\text{max}_\sigma(s) = \{ \pi \in \Pi^\text{max}(s) \mid \forall i \in \{1, \ldots, \ell(\pi)\}. \exists a \in \text{next}_\sigma(\pi_{i-1}). \pi_{i-1} \xrightarrow{a} \pi_i \}.
\]

**Definition 5** (Winning Strategy). Let \(G = (S, A_1, A_2, \rightarrow, \text{Goal})\) be a GLTS and \(s \in S\) be a state. A strategy \(\sigma\) is a winning strategy for player 1 at \(s\) in \(G\) iff for all \(\pi \in \Pi^\text{max}_\sigma(s)\) there exists a position \(i\) s.t. \(\pi_i \in \text{Goal}\).

If a state is winning for player 1 in \(G\) then no matter what action sequence the environment chooses, eventually a goal state is reached. Furthermore, for a given winning strategy \(\sigma\) at \(s\) in \(G\) there is a finite number \(n \in \mathbb{N}\) such that a goal state is always reached with at most \(n\) action firings. We call the minimum such number the strategy depth of \(\sigma\).

**Definition 6** (Strategy Depth). Let \(G = (S, A_1, A_2, \rightarrow, \text{Goal})\) be a GLTS, \(s \in S\) a winning state for player 1 in \(G\) where \(s \notin \text{Goal}\), and \(\sigma\) a winning strategy at \(s\) in \(G\). Then \(n \in \mathbb{N}^0\) is the depth of \(\sigma\) at \(s\) in \(G\) if:

1. for all \(\pi \in \Pi^\text{max}_{\Pi_{\sigma}}(s)\) there exists \(0 \leq i \leq n\) s.t. \(\pi_i \in \text{Goal}\), and
2. there exists \(\pi' \in \Pi^\text{max}_{\Pi_{\sigma}}(s)\) s.t. \(\pi'_n \in \text{Goal}\) and for all \(0 \leq j < n\) we have \(\pi'_j \notin \text{Goal}\).

**Lemma 7.** Let \(G = (S, A_1, A_2, \rightarrow, \text{Goal})\) be a GLTS, \(s \in S\) a winning state for player 1 in \(G\), and \(\sigma\) a winning strategy at \(s\) in \(G\).

1. There exists \(n \in \mathbb{N}^0\) that is the depth of \(\sigma\) at \(s\) in \(G\).
2. For all \(a \in \text{next}_\sigma(s)\) where \(s \xrightarrow{a} s'\), the depth of \(\sigma\) at \(s'\) in \(G\) is \(m\) such that \(0 \leq m < n\).

A set of actions for a given state and a given set of goal states is called an interesting set if for any path leading to any goal state at least one action from the set of interesting actions has to be fired.

**Definition 8** (Interesting Actions). Let \(G = (S, A_1, A_2, \rightarrow, \text{Goal})\) be a GLTS and \(s \in S\) a state. A set of actions \(A_s(\text{Goal}) \subseteq A\) is called an interesting set of actions for \(s\) and \(\text{Goal}\) if whenever \(s \notin \text{Goal}\), \(w = a_1 \cdots a_n \in A^*\), \(s \xrightarrow{w} s'\), and \(s' \in \text{Goal}\) then there exists \(1 \leq i \leq n\) s.t. \(a_i \in A_s(\text{Goal})\).

**Example 9.** In Figure 1 we see an example of a GLTS \(G = (S, A_1, A_2, \rightarrow, \text{Goal})\) where \(S = \{s_1, s_2, s_3, s_4, s_5, s_6, s_7\}\) is the states denoted by a circle, \(A_1 = \{a, b, c\}\) is the player 1 actions, \(A_2 = \{d\}\) is the player 2 actions, and \(\rightarrow\) is denoted by the solid and dashed lines between states and labelled with a corresponding action for player 1 and 2, respectively. Let \(\text{Goal} = \{s_6\}\).

We consider different proposals for a set of interesting actions for the state \(s_1\). The set \(\{b\}\) is an interesting set of actions in \(s_1\) since the goal state \(s_6\) cannot be reached without firing \(b\) at least once. Furthermore, the sets \(\{a\}\) and \(\{c\}\) are also sets of interesting actions for the state \(s_1\).

Player 1 has to consider his safe actions. A player 1 action is safe in a given player 1 state if by firing it before any sequence of player 1 actions excluding the safe action then it will never reach a player 2 state.
Definition 10 (Safe Action). Let $G = (S, A_1, A_2, \rightarrow, \text{Goal})$ be a GLTS and $s \in S$ a state s.t. $\text{en}_2(s) = \emptyset$. An action $a \in A_1 \cap \text{en}_1(s)$ is safe in $s$ if whenever $w \in (A_1 \setminus \{a\})^*$ and $s \xrightarrow{w} s'$ and $\text{en}_2(s') = \emptyset$ and $s \xrightarrow{aw} s''$ then $\text{en}_2(s'') = \emptyset$. The set of all safe actions for $s$ is written as $\text{safe}(s)$.

Example 11. Consider again the GLTS in Figure 1. We reasoned in Example 9 that the set $\{b\}$ is an interesting set of actions in the state $s_1$. However, $b$ is not a safe player 1 action in $s_1$ since by definition $b$ has to be enabled at $s_1$ to be safe. The enabled actions at $s_1$ is $\text{en}(s_1) = \{a, c\}$, and between these two actions only $a$ is safe. The action $c$ is not safe since we have $s_1 \xrightarrow{a} s_2$ and $\text{en}_2(s_2) = \emptyset$ but $s_1 \xrightarrow{ca} s_5$ and $\text{en}_2(s_5) \neq \emptyset$. It is clear from the figure that $s_1$ is a winning state for player 1 with $a$ as the action player 1 should choose in order to win.

3 Stable Reduction

A reduction $\text{St}$ provides at each state a set of actions which are sufficient to fire such that a certain property is preserved in the reduced game. In the game setting, we have to guarantee the preservation of winning strategies for both players in the game. In what follows, we shall introduce a number of conditions that preserve winning strategies and we call such a reduction a stable one.

For the remainder of the section let $s \in S$ be a state and $\text{Goal} \subseteq S$ be a set of goal states, and let $A_2(\text{Goal})$ be a fixed set of interesting actions for $s$ and $\text{Goal}$.

Definition 12 (Stable Strategy Conditions). A reduction $\text{St}$ is called stable if $\text{St}$ satisfies for every $s \in S$ Conditions I, W, R, G1, G2, S, C, and D.

I If $\text{en}_1(s) \neq \emptyset$ and $\text{en}_2(s) \neq \emptyset$ then $\text{en}(s) \subseteq \text{St}(s)$.

W For all $w \in \overline{\text{St}}(s)$ and all $a \in \text{St}(s)$ if $s \xrightarrow{aw} s'$ then $s \xrightarrow{aw} s'$.

R $A_2(\text{Goal}) \subseteq \text{St}(s)$

G1 For all $w \in \overline{\text{St}}(s)$ if $\text{en}_2(s) = \emptyset$ and $s \xrightarrow{w} s'$ then $\text{en}_2(s') = \emptyset$.

G2 For all $w \in \overline{\text{St}}(s)$ if $\text{en}_1(s) = \emptyset$ and $s \xrightarrow{w} s'$ then $\text{en}_1(s') = \emptyset$.

S $\text{en}_1(s) \cap \text{St}(s) \subseteq \text{safe}(s)$ or $\text{en}_1(s) \subseteq \text{St}(s)$

C For all $a \in A_2$ if there exists $w \in A_2^\infty$ s.t. $s \xrightarrow{w}$ and $a$ occurs infinitely often in $w$ then $a \in \text{St}(s)$.

D If $\text{en}_2(s) \neq \emptyset$ then there exists $a \in \text{en}_2(s) \cap \text{St}(s)$ s.t. for all $w \in \overline{\text{St}}(s)$ where $s \xrightarrow{w} s'$ we have $a \in \text{en}_2(s')$.
If \( s \) is a mixed state then Condition I ensures all enabled actions are included in the reduction. That is, we do not attempt to reduce the state space from this state. Condition W ensures that we can swap the ordering of firing actions, such that firing the actions included in the reduction first still ensures we can reach a given state, i.e. they are independent. Condition R ensures that a goal state cannot be reached solely by exploring actions not in the reduction, i.e. reachability of paths to goal states are preserved in the reduction. Conditions G1 and G2 ensure that if a state is a player 1 (or player 2) state then a player 2 (or player 1) state cannot be reached solely by exploring actions not in the reduction, i.e. reachability of paths to mixed states and opposing player states are preserved in the reduction. Condition S ensures either that all stubborn player 1 actions are also safe and if this is not the case then all player 1 actions are included in the reduction. Condition C preserves infinite paths on which only player 2 actions are fired. Condition D ensures that at least one player 2 action cannot be disabled solely by exploring actions not in the reduction.

**Example 13.** In Figure 2 we see an example of a GLTS \( G = (S, A_1, A_2, \rightarrow, \text{Goal}) \) where \( S = \{s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8, s_9, s_{10}\} \) are the states denoted by a circle, \( A_1 = \{a, b, c, d\} \) is the player 1 actions, \( A_2 = \{e\} \) is the player 2 action, and \( \rightarrow \) is denoted by the solid and dashed lines between states and labelled with a corresponding action for player 1 and 2, respectively. Let \( \text{Goal} = \{s_8\} \) be a fixed set of goal states for this GLTS and \( A_{s_1}(\text{Goal}) = \{a\} \) be a set of interesting actions. Thick lines indicate transitions and states that are preserved by a stable reduction \( St \), while thin lines indicates transitions and states that are removed by the same reduction. For state \( s_1 \) we have \( St(s_1) = \{a, c\} \) as it is sufficient to satisfy the stable reduction conditions. We satisfy G1 since \( c \) has to be fired once to reach \( s_7 \). For \( s_1 \xrightarrow{b_0} s_5 \) and \( s_1 \xrightarrow{b_1} s_7 \) we also have \( s_1 \xrightarrow{ab} s_5 \) and \( s_1 \xrightarrow{cd} s_7 \), so W is satisfied. Clearly \( St(s_1) \) is an interesting set since \( A_{s_1}(\text{Goal}) \subseteq St(s_1) \), so R is satisfied. Condition S is satisfied since \( St(s_1) \cap en(s_1) \subseteq safe(s_1) \). We have that I, G2, C, and D are satisfied as well since their antecedents are not true.

![Figure 2](image-url) Example of a stable reduction for a state \( s_1 \).

We shall first notice the fact that if a goal state is reachable from some state, then the state has at least one enabled action that is also in the stubborn set.

**Lemma 14.** Let \( G = (S, A_1, A_2, \rightarrow, \text{Goal}) \) be a GLTS, \( St \) a reduction that satisfies Conditions W and R, and \( s \in S \) a state. If there exists \( w \in A^* \) s.t. \( s \xrightarrow{w} s' \) and \( s' \in \text{Goal} \) then \( St(s) \cap en(s) \neq \emptyset \).

The correctness of stable stubborn reductions is proved by the next two lemmas. Both lemmas are proved by induction on the depth of a winning strategy for player 1 in the game.
Lemma 15. Let $G = (S, A_1, A_2, \rightarrow, \text{Goal})$ be a GLTS and $St$ a stable reduction. For all $s \in S$ if state $s$ is winning for player 1 in $G$ then state $s$ is winning for player 1 in $G_{St}$.

Lemma 16. Let $G = (S, A_1, A_2, \rightarrow, \text{Goal})$ be a GLTS and $St$ a stable reduction. For all $s \in S$ if state $s$ is winning for player 1 in $G_{St}$ then state $s$ is winning for player 1 in $G$.

We can now present the main theorem showing that stable reductions preserve the winning strategies of both players in the game.

Theorem 17 (Strategy Preservation for GLTS). Let $G = (S, A_1, A_2, \rightarrow)$ be a GLTS and $St$ a stable reduction. For all $s \in S$ state $s$ is winning for player 1 in $G$ iff state $s$ is winning for player 1 in $G_{St}$.

Moreover, for non-mixed games we can simplify the conditions of stable reductions by removing the requirement on safe actions.

Theorem 18 (Strategy Preservation for Non-Mixed GLTS). Let $G = (S, A_1, A_2, \rightarrow)$ be a non-mixed GLTS and $St$ a stable reduction with Condition $S$ excluded. For all $s \in S$ state $s$ is winning for player 1 in $G$ iff state $s$ is winning for player 1 in $G_{St}$.

4 Stable Reductions on Petri Net Games

We now introduce the formalism of Petri net games and show how to algorithmically construct stable reductions in a syntax-driven manner.

Definition 19 (Petri Net Game). A Petri net game is a tuple $N = (P, T_1, T_2, W, I)$ where $P$ and $T = T_1 \cup T_2$ are finite sets of places and transitions, respectively, such that $P \cap T = \emptyset$ and where transitions are partitioned into player 1 and player 2 transitions, $W : (P \times T) \cup (T \times P) \rightarrow \mathbb{N}^0$ is a weight function for regular arcs, and $I : (P \times T) \rightarrow \mathbb{N}^\infty$ is a weight function for inhibitor arcs. A marking $M$ on $N$ is a function $M : P \rightarrow \mathbb{N}^0$. The set $M(N)$ is the set of all markings for $N$.

For the rest of this section, let $N = (P, T_1, T_2, W, I)$ be a fixed Petri net game such that $T = T_1 \cup T_2$. Let us first fix some useful notation. For a place or transition $x$, we denote the preset of $x$ as $\bullet x = \{y \in P \cup T \mid W((y, x)) > 0\}$, and the postset of $x$ as $x^\bullet = \{y \in P \cup T \mid W((x, y)) > 0\}$. For a transition $t$, we denote the inhibitor preset of $t$ as $\circ t = \{p \in P \mid I((p, t)) \neq \infty\}$, and the inhibitor postset of a place $p$ as $p^\circ = \{t \in T \mid I((p, t)) \neq \infty\}$. For a place $p$ we define the increasing preset of $p$, containing all transitions that increase the number of tokens in $p$, as $\uparrow p = \{t \in \bullet p \mid W((t, p)) > W((p, t))\}$, and similarly the decreasing postset of $p$ as $p^\downarrow = \{t \in \circ p \mid W((t, p)) < W((p, t))\}$. For a transition $t$ we define the decreasing preset of $t$, containing all places that have their number of tokens decreased by $t$, as $\downarrow t = \{p \in \circ t \mid W((p, t)) > W((t, p))\}$, and similarly the increasing postset of $t$ as $t^\uparrow = \{p \in \bullet t \mid W((t, p)) < W((p, t))\}$. For a set $X$ of either places or transitions, we extend the notation as $\bullet X = \bigcup_{x \in X} \bullet x$ and $X^\bullet = \bigcup_{x \in X} x^\bullet$, and similarly for the other operators.

A Petri net $N = (P, T_1, T_2, W, I)$ defines a GLTS $G(N) = (S, A_1, A_2, \rightarrow, \text{Goal})$ where $S = M(N)$ is the set of all markings, $A_1 = T_1$ is the set of player 1 actions, $A_2 = T_2$ is the set of player 2 actions, $M \xrightarrow{\nu} M'$ whenever for all $p \in P$ we have $M(p) \geq W((p, t))$, $M(p) < I((p, t))$ and $M'(p) = M(p) - W((p, t)) + W((t, p))$, and $\text{Goal} \in M(N)$ is the set of goal markings, described by a simple reachability logic formula defined below.

By analysing the increasing presets and postsets, we can identify a sufficient condition for a transition to be safe.
Table 1 Increasing and decreasing transitions for expression \( e \in E_N \).

<table>
<thead>
<tr>
<th>Expression ( e )</th>
<th>( \text{incr}_M(e) )</th>
<th>( \text{decr}_M(e) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c )</td>
<td>( \emptyset )</td>
<td>( \emptyset )</td>
</tr>
<tr>
<td>( p )</td>
<td>( p )</td>
<td>( p )</td>
</tr>
<tr>
<td>( e_1 + e_2 )</td>
<td>( \text{incr}_M(e_1) \cup \text{incr}_M(e_2) )</td>
<td>( \text{decr}_M(e_1) \cup \text{decr}_M(e_2) )</td>
</tr>
<tr>
<td>( e_1 - e_2 )</td>
<td>( \text{incr}_M(e_1) \cup \text{decr}_M(e_2) )</td>
<td>( \text{decr}_M(e_1) \cup \text{incr}_M(e_2) )</td>
</tr>
<tr>
<td>( e_1 \cdot e_2 )</td>
<td>( \text{incr}_M(e_1) \cup \text{decr}_M(e_1) \cup \text{incr}_M(e_2) \cup \text{decr}_M(e_2) )</td>
<td>( \text{incr}_M(e_2) \cup \text{decr}_M(e_2) )</td>
</tr>
</tbody>
</table>

\[ \text{Lemma 20 (Safe Transition).} \] Let \( N = (P,T_1,T_2,W,I) \) be a Petri net and \( t \in T \) a transition. If \( t^+ \cap \cdot T_2 = \emptyset \) and \( -t \cap \cdot T_2 = \emptyset \) then \( t \) is safe in any marking of \( N \).

Let \( E_N \) be the set of marking expressions in \( N \) given by the abstract syntax (here \( e \) ranges over \( E_N \)):
\[ e ::= c \mid p \mid e_1 \oplus e_2 \]
where \( c \in \mathbb{N}^0 \), \( p \in P \), and \( \oplus \in \{+,-,\ast\} \). An expression \( e \in E_N \) is evaluated relatively to a marking \( M \in \mathcal{M}(N) \) by the function \( \text{eval}_M : E_N \to \mathbb{Z} \) where \( \text{eval}_M(c) = c \), \( \text{eval}_M(p) = M(p) \) and \( \text{eval}_M(e_1 \oplus e_2) = \text{eval}_M(e_1) \oplus \text{eval}_M(e_2) \).

In Table 1 we define the functions \( \text{incr}_M : E_N \to 2^T \) and \( \text{decr}_M : E_N \to 2^T \) that, given an expression \( e \in E_N \), return the set of transitions that can (when fired) increase resp. decrease the evaluation of \( e \).

\[ \text{Lemma 21 ([4]).} \] Let \( N = (P,T_1,T_2,W,I) \) be a Petri net and \( M \in \mathcal{M}(N) \) a marking. Let \( e \in E_N \) and let \( M \overrightarrow{\ast} M' \) where \( w = t_1 t_2 \ldots t_n \in T^* \).
\[ = \text{If } \text{eval}_M(e) < \text{eval}_{M'}(e) \text{ then there is } i, 1 \leq i \leq n, \text{ such that } t_i \in \text{incr}_M(e). \]
\[ = \text{If } \text{eval}_M(e) > \text{eval}_{M'}(e) \text{ then there is } i, 1 \leq i \leq n, \text{ such that } t_i \in \text{decr}_M(e). \]

We can now define the set of reachability formulae \( \Phi_N \) that evaluate over the markings in \( N \) as follows:
\[ \varphi ::= \text{true} \mid \text{false} \mid t \mid e_1 \bowtie e_2 \mid \text{deadlock} \mid \varphi_1 \land \varphi_2 \mid \varphi_1 \lor \varphi_2 \mid \neg \varphi \]
where \( e_1, e_2 \in E_N, t \in T \) and \( \bowtie \in \{<,\leq,=,\neq,\geq,\} \).

The satisfaction relation for a formula \( \varphi \in \Phi_N \) in a marking \( M \) is defined as expected:
\[ M \models t \quad \text{iff } t \in en(M) \]
\[ M \models e_1 \bowtie e_2 \quad \text{iff } \text{eval}_M(e_1) \bowtie \text{eval}_M(e_2) \]
\[ M \models \text{deadlock} \quad \text{iff } en(M) = \emptyset \]
\[ M \models \varphi_1 \land \varphi_2 \quad \text{iff } M \models \varphi_1 \text{ and } M \models \varphi_2 \]
\[ M \models \varphi_1 \lor \varphi_2 \quad \text{iff } M \models \varphi_1 \text{ or } M \models \varphi_2 \]
\[ M \models \neg \varphi \quad \text{iff } M \not\models \varphi \]

Our aim is to be able to preserve at least one execution to the set \( \text{Goal} = \{ M \in \mathcal{M}(N) \mid M \models \varphi \} \) for a given formula \( \varphi \) describing the set of goal markings. In order to achieve this, we define the set of interesting transitions \( A_M(\varphi) \) for a formulae \( \varphi \) so that any firing sequence of transitions from a marking that does not satisfy \( \varphi \) leading to a marking that satisfies \( \varphi \) must contain at least one interesting transition. Table 2 provides the definition of \( A_M(\varphi) \).
possible infinite cycle transitions. Finally, every transition from the set $\text{MarkedPlaces}$ of possible places that can be marked by firing $T_2$ transitions from $M$. Finally, every transition from the set $\text{Inf}$ that has its preset marked is added to the set of possible infinite cycle transitions.

that is similar to the one presented in [4] for the non-game setting, except for the conjunction where we in our setting use Equation (1) that provides an optimisation for Condition $\text{S}$ and possibly ends with a smaller set of interesting transitions.

$A_M(\varphi_1 \land \varphi_2) = \begin{cases} 
A_M(\varphi_1) & \text{if } M \models \varphi_2 \\
A_M(\varphi_2) & \text{if } M \models \varphi_1 \\
A_M(\varphi_1) & \text{if } M \models \varphi_1 \text{ and } A_M(\varphi_1) \subseteq \text{safe}(M) \\
A_M(\varphi_2) & \text{if } M \models \varphi_2 \text{ and } A_M(\varphi_2) \subseteq \text{safe}(M) \\
A_M(\varphi_1) \cup A_M(\varphi_2) & \text{otherwise} 
\end{cases}$ (1)

The desired property of the set of interesting transitions is formulated below.

$\textbf{Lemma 22.}$ Let $N = (P,T_1,T_2,W,I)$ be a Petri net, $M \in \mathcal{M}(N)$ a marking, and $\varphi \in \Phi_N$ a formula. If $M \not\models \varphi$ and $M \xrightarrow{w} M'$ where $w \in A_M(\varphi)$ then $M' \not\models \varphi$.

We shall now discuss a method for detecting the impossibility of infinite firing sequences consisting of purely player 2 transitions. Let $\text{Fin} \subseteq P \cup T_2$ be the smallest set that for every $p \in P$ and every $t \in T_2$ satisfies:

1. $p \in \text{Fin}$ whenever $W((p,t)) > W((t,p))$ for every $t \in \bullet p \cap T_2$,
2. $t \in \text{Fin}$ whenever $\neg t \cap \text{Fin} \neq \emptyset$, and
3. $p \in \text{Fin}$ whenever $\bullet p \cap T_2 \subseteq \text{Fin}$.

It is easy to observe that by performing any infinite firing sequence of $T_2$ transitions, only finitely many tokens can be added to any place from $\text{Fin}$ and the infinite firing sequence contains only finitely many occurrences of any transition from $\text{Fin}$. We let $\text{Inf} = (P \cup T_2) \setminus \text{Fin}$ denote the complement of the set $\text{Fin}$. Note that $\text{Fin}$ and $\text{Inf}$ only has to be computed once as it is independent of any specific marking.

In Algorithm 1 we present an overapproximation algorithm for detecting cycles of player 2 transitions. The algorithm first checks for orphan transitions (with empty preset) and includes them to the cycle transitions. Then, for a given marking $M$, it overapproximates the set $\text{MarkedPlaces}$ of possible places that can be marked by firing $T_2$ transitions from $M$. Finally, every transition from the set $\text{Inf}$ that has its preset marked is added to the set of possible infinite cycle transitions.

\begin{table}[h]
\centering
\caption{Interesting transitions of $\varphi$ (assuming $M \not\models \varphi$, otherwise $A_M(\varphi) = \emptyset$).
\begin{tabular}{l|l|l}
\hline
$\varphi$ & $A_M(\varphi)$ & $A_M(\neg \varphi)$ \\
\hline
$\text{deadlock}$ & $(\bullet t)^{-} \cup \langle \langle \bullet t \rangle$ for some $t \in \text{en}(M)$ & $\emptyset$ \\
$t$ & $\langle t \rangle^{+}$ for some $p \in T$ where $M(p) < W((p,t))$ or $p^{-}$ for some $p \in T$ where $M(p) \geq W((p,t))$ & $(\bullet t)^{-} \cup \langle \langle \bullet t \rangle$ \\
$e_1 < e_2$ & $\text{decr}_M(e_1) \cup \text{incr}_M(e_2)$ & $A_M(e_1 \geq e_2)$ \\
$e_1 \leq e_2$ & $\text{decr}_M(e_1) \cup \text{incr}_M(e_2)$ & $A_M(e_1 > e_2)$ \\
$e_1 > e_2$ & $\text{incr}_M(e_1) \cup \text{decr}_M(e_2)$ & $A_M(e_1 < e_2)$ \\
$e_1 \geq e_2$ & $\text{incr}_M(e_1) \cup \text{decr}_M(e_2)$ & $A_M(e_1 \leq e_2)$ \\
$e_1 \neq e_2$ & $\text{decr}_M(e_1) \cup \text{incr}_M(e_2)$ if $\text{eval}_M(e_1) > \text{eval}_M(e_2)$ or $\text{incr}_M(e_1) \cup \text{decr}_M(e_2)$ if $\text{eval}_M(e_1) < \text{eval}_M(e_2)$ & $A_M(e_1 \neq e_2)$ \\
$\varphi_1 \land \varphi_2$ & Defined in Equation (1) & $A_M(\neg \varphi_1 \lor \neg \varphi_2)$ \\
$\varphi_1 \lor \varphi_2$ & $A_M(\varphi_1) \cup A_M(\varphi_2)$ & $A_M(\neg \varphi_1 \land \neg \varphi_2)$ \\
\end{tabular}
\end{table}
23:10 Partial Order Reduction for Reachability Games

Algorithm 1: cycle(N, M): Overapproximation algorithm for computing the set of transitions that may appear in infinite player 2 computations.

- **input**: N = (P, T1, T2, W, I) and M ∈ M(N)
- **output**: If a transition t ∈ T2 appears infinitely often on some infinite firing sequence of T2 transitions from the marking M then t ∈ cycle(N, M).

1. CycleTransitions := ∅;
2. foreach t ∈ T2 do
   3.   if *t = ∅ then
       4.     CycleTransitions := CycleTransitions ∪ {t};
3. FreshPlaces := {p ∈ P | M(p) > 0}; MarkedPlaces := ∅;
4. while MarkedPlaces ≠ FreshPlaces do
   5.   MarkedPlaces := FreshPlaces;
6.   foreach p ∈ P \ MarkedPlaces do
   7.     if ∃t ∈ T2, p ∈ *t ∧ *t ⊆ MarkedPlaces then
       8.       FreshPlaces := FreshPlaces ∪ {p};
   9.   foreach t ∈ Inf ∩ T2 do
      10.   if *t ⊆ MarkedPlaces then
           11.     CycleTransitions := CycleTransitions ∪ {t};
      12.   return CycleTransitions;

**Lemma 23.** Let N = (P, T1, T2, W, I) be a Petri net game and M ∈ M(N). Algorithm 1 terminates and if there exists w ∈ T2 such that M −→ w where t ∈ T2 occurs infinitely often in w then t ∈ cycle(N, M).

We can now provide a list of syntactic conditions that guarantee the stability of a given reduction.

**Theorem 24 (Stable Reduction Preserving Closure).** Let N = (P, T1, T2, W, I) be a Petri net game, φ a formula, and St a reduction of G(N) such that for all M ∈ M(N) the following conditions hold.

1. If en1(M) ≠ ∅ and en2(M) ≠ ∅ then en(M) ⊆ St(M).
2. If en1(M) ∩ St(M) ⊆ safe(M) then en1(M) ⊆ St(M).
3. M(φ) ⊆ St(M)
4. If en1(M) = ∅ then T1 ⊆ St(M).
5. If en2(M) = ∅ then T2 ⊆ St(M).
6. cycle(N, M) ⊆ St(M)
7. For all t ∈ St(M) if t ∉ en(M) then either
   a. there exists p ∈ *t s.t. M(p) < W((p, t)) and +p ⊆ St(s), or
   b. there exists p ∈ ♦t s.t. M(p) ≥ I((p, t)) and p − ⊆ St(s).
8. For all t ∈ St(M) if t ∈ en(M) then
   a. for all p ∈ −t we have p∗ ⊆ St(M), and
   b. for all p ∈ t+ we have p+ ⊆ St(M).
9. If en2(M) ≠ ∅ then there exists t ∈ en2(M) ∪ St(M) s.t. (♦t)− ∪ (+t) ⊆ St(M).

Then St satisfies I, W, R, G1, G2, S, C, and D.
Algorithm 2: Computation of $St(M)$ for some stable reduction $St$.

\begin{algorithm}
\begin{algorithmic}[1]
\Require A Petri net game $N = (P,T_1,T_2,W,I)$ and $M \in M(N)$ and formula $\varphi$
\Ensure $X \subseteq T$ where $X$ is a stable stubborn set for $M$
\If{$en(M) = \emptyset$} 
\State return $T$;
\EndIf
\If{$en_1(M) \neq \emptyset \land en_2(M) \neq \emptyset$} 
\State return $T$;
\EndIf
\State $Y := \emptyset$
\If{$en_1(M) = \emptyset$} 
\State Pick any $t \in en_2(M)$;
\State $Y := T_1 \cup (\cdot t)^- \cup (+t)$;
\State $Y := Y \cup \text{cycle}(N,M)$;
\Else
\State $Y := T_2$
\State $Y := Y \cup A_M(\varphi)$;
\State $X := \text{Saturate}(Y)$;
\If{$X \cap en_1(M) \not\subseteq \text{safe}(M)$} 
\State return $T$;
\EndIf
\EndIf
\State return $X$;
\end{algorithmic}
\end{algorithm}

In Algorithm 2 we provide a pseudocode for calculating stubborn sets for a given marking. The algorithm calls Algorithm 3 that saturates a given set to satisfy Conditions 7 and 8.

\textbf{Theorem 25.} Algorithm 2 terminates and returns $St(M)$ for some stable reduction $St$.

\textbf{Remark 26.} In the actual implementation of the algorithm, we first saturate only over the set of interesting transitions and in the case that $\text{Saturate}(A_M(\varphi)) \cap en(M) = \emptyset$, we do not explore any of the successors of the marking $M$ as we know that no goal marking can be reached from $M$ (this follows from Lemma 14).

\section{Implementation and Experiments}

We extend the Petri net verification engine \texttt{verifypn} [12], a part of TAPAAL tool suite [6], to experimentally demonstrate the viability of our approach. The synthesis algorithm for solving Petri net games is an adaptation of the dependency graph fixed-point computation from [15, 14] that we reimplement in C++ while utilising PTries [13] for efficient state storage. The source code is available under GPLv3 [3]. We conduct a series of experiments using the following scalable case studies.

- In \textit{Autonomous Intersection Management} (AIM) vehicles move at different speeds towards an intersection and we want to ensure the absence of collisions. We model the problem as a Petri net game and refer to each instance as AIM-W-X-Y-Z where $W$ is the number of intersections with lanes of length $X$, $Z$ is the number of cars, and $Y$ is the number of different speeds for each car. The controller assigns speeds to cars while the environment aims to cause a collision. The goal marking is where all cars reach their destinations while there are no collisions.

- We reformulate the classical \textit{Producer Consumer System} (PCS) as a Petri net game. In each instance PCS-N-K the total of $N$ consumers (controlled by the environment) and $N$ producers (controlled by the controller) share $N$ buffers. Each consumer and producer has
Algorithm 3: Saturate($Y$).

1. \( X := \emptyset \);
2. while \( Y \neq \emptyset \) do
3. \( \text{Pick any } t \in Y \)
4. if \( t \notin \text{en}(M) \) then
5. if \( \exists p \in t. M(p) < W((p, t)) \) then
6. \( \text{Pick any } p \in t \text{ s.t. } M(p) < W((p, t)) \)
7. \( Y := Y \cup (+p \setminus X) \);
8. else
9. \( \text{Pick any } p \in t \text{ s.t. } M(p) \geq I((p, t)) \)
10. \( Y := Y \cup (p^- \setminus X) \);
11. else
12. \( Y := Y \cup ((t^-) \cup (t^+) \setminus X) \);
13. \( X := X \cup \{t\} \);
14. \( Y := Y \setminus \{t\} \);
15. return \( X \);

A fixed buffer to consume/produce from/to, and each consumer/producer has \( K \) different randomly chosen consumption/production rates. The game alternates in rounds where the player choose for each consumer/producer appropriate buffers and rates. The goal of the game is to ensure that the consumers have always enough products in the selected buffers while at the same time the buffers have limited capacity and may not overflow.

- The Railway Scheduling Problem contains four instances modelling the Danish train station Lyngby and three of its smaller variants. The scheduling problem, including the station layout, was originally described as a game in [16] and each instance is annotated by a number \( N \) representing the number of trains that migrate through the railway network. The controller controls the lights and switches, while the environment moves the trains. The goal of the controller is to make sure that all trains reach (without any collisions) their final destinations.

- The Nim (NIM-K-S) Petri net game was described in [22] as a two player game where the players in rounds repeatedly remove between 1 and \( K \) pebbles from an initial stack containing \( S \) pebbles. The player that has a turn and empty stack of pebbles loses. In our (equivalent) model, we are instead adding pebbles and the player that first adds to or above the given number \( S \) loses.

- The Manufacturing Workflow (MW) contains instances of a software product line Petri net model presented in [20]. The net describes a series of possible ways of configuring a product (performed by the environment) while the controller aims to construct a requested product. The model instance MW-N contains \( N \) possible choices of product features.

- The Order Workflow (OW) Petri net game model is taken from [8] and the goal of the game is to synthesise a strategy that guarantees a workflow soundness, irrelevant of the choices made by the environment. We scale the workflow by repeatedly re-initialising the workflow \( N \) times (denoted by OW-N).

All experimental evaluation is run on AMD Opteron 6376 Processors with 120 GB memory limitation and 12 hours timeout (we measure only the execution time without the parsing time of the models). We use for all experiments the depth first search strategy and we only
Table 3 Experiments with and without partial order reduction (POR and NORMAL).

<table>
<thead>
<tr>
<th>Model</th>
<th>Time (seconds)</th>
<th>Markings ×1000</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIM-13-100-6-11</td>
<td>117.9</td>
<td>1702</td>
<td>60%</td>
</tr>
<tr>
<td>AIM-13-100-6-16</td>
<td>173.9</td>
<td>2464</td>
<td>64%</td>
</tr>
<tr>
<td>AIM-13-150-9-16</td>
<td>337.0</td>
<td>3696</td>
<td>35%</td>
</tr>
<tr>
<td>AIM-13-150-9-21</td>
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<td>4853</td>
<td>28%</td>
</tr>
<tr>
<td>AIM-14-150-9-16</td>
<td>449.9</td>
<td>4259</td>
<td>38%</td>
</tr>
<tr>
<td>AIM-15-150-9-16</td>
<td>534.5</td>
<td>4861</td>
<td>28%</td>
</tr>
<tr>
<td>PCS-2-2</td>
<td>24.0</td>
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<td>17%</td>
</tr>
<tr>
<td>PCS-2-3</td>
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<td>22%</td>
</tr>
<tr>
<td>PCS-2-4</td>
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<td>240510</td>
<td>29%</td>
</tr>
<tr>
<td>LyngbySmall-2</td>
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<td>1803</td>
<td>71%</td>
</tr>
<tr>
<td>LyngbySmall-3</td>
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<td>11473</td>
<td>-13%</td>
</tr>
<tr>
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</tr>
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</tr>
<tr>
<td>NIM-11-49500</td>
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<td>533516</td>
<td>99%</td>
</tr>
<tr>
<td>MW-40</td>
<td>735.3</td>
<td>69439</td>
<td>9%</td>
</tr>
<tr>
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</tr>
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<td>OW-10000000</td>
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<td>32000</td>
<td>20%</td>
</tr>
</tbody>
</table>

report the examples where the algorithms both with and without partial order reduction returned a result within the time and memory limits. We provide a reproducibility package with all models and experimental data [3].

5.1 Results

Table 3 shows the experimental evaluation, displaying the relative gain in computation time (in seconds) without and with partial order reduction as well in the number of explored markings (in thousands). The results demonstrate significant reductions across all models, in some cases like in NIM and MW even of several degrees of magnitude. Other models like PCS, AIM and OW show a moderate but significant reduction. We observe that the time reduction is generally only few percent smaller than the reduction in the number of explored markings, showing typically between 2% to 20% overhead for computing (on-the-fly) the stubborn sets. For two instances of the LyngbySmall models we notice an actual slowdown in the running time where for LyngbySmall-3 the number of reduced markings is less significant and it results in 13% slowdown, partially due to the overhead for computing stubborn sets but also because the search strategy changed and this resulted in the fact that we have to search a larger portion of the generated dependency graph before we obtain a conclusive answer. This effect is, in particular, observed in the LyngbySmall-4 example where the
Partial Order Reduction for Reachability Games

number of markings stored when applying partial order reduction actually exceeds those
where no reduction is applied. Nevertheless, in general the experiments confirm the practical
applicability of partial order reduction for 2-player games with only minimal overhead for
computing the stubborn sets.

6 Conclusion

We generalised the partial order reduction technique based on stubborn sets from plain
reachability to a game theoretical setting. This required a nontrivial extension of the classical
conditions on stubborn sets so that a state space reduction can be achieved for both players
in the game. In particular, the computation of the stubborn sets for player 2 (uncontrollable
transitions) needed a new insight on how to handle and efficiently approximate the existence
of infinite runs with player 2 transitions only. We proved the correctness of our approach and
instantiated it to the case of Petri net games. We provided (to the best of our knowledge)
the first implementation of partial order reduction for Petri net games and made it available
as a part of the model checker TAPAAL. The experiments show promising results on a
number of case studies, achieving in general a substantial state space reduction with only a
small overhead for computing the stubborn sets. In the future work, we plan to combine our
contribution with a recent insight on how to effectively use partial order reduction in the
timed setting [4] in order to extend our framework to general timed games.

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