

Abstract

It is well-known that deciding consistency for normal answer set programs (ASP) is NP-complete, thus, as hard as the satisfaction problem for propositional logic (SAT). The exponential time hypothesis (ETH) implies that the best algorithms to solve these problems take exponential time in the worst case. However, accounting for the treewidth, the consistency problem for ASP is slightly harder than SAT; while SAT can be solved by an algorithm that runs in exponential time in the treewidth $k$, normal ASP requires exponential time in $k \cdot \log(k)$. This extra cost is due to checking that there are no self-supported true atoms because of positive cycles in the program. In this paper, we refine this recent result and show that consistency for ASP can be decided in exponential time in $k \cdot \log(\iota)$ where $\iota$ is a novel measure, bounded by both treewidth $k$ and the size $\ell$ of the largest strongly-connected component of the positive dependency graph of the program. We provide a treewidth-aware reduction from ASP to SAT that adheres to the above limit.

1 Introduction

Answer Set Programming (ASP) (Brewka, Eiter, and Truszczynski 2011; Gebser et al. 2012) is a problem modeling and solving paradigm well-known in the area of knowledge representation and reasoning that is experiencing an increasing number of successful applications (Balduccini, Gelfond, and Noguera 2006; Noguera et al. 2001; Guziolowski et al. 2013). The flexibility of ASP comes with a high computational complexity cost: its consistency problem, that is, deciding the existence of a solution (answer set) for a given logic program is $\Sigma^P_2$-complete (Eiter and Gottlob 1995), in general. Fragments with lower complexity are also known. For instance, the consistency problem for normal, head-cycle-free (HCF), or tight ASP is NP-complete. Even for solving this class of programs, the best known algorithms require exponential time with respect to the size of the program. Still, existing solvers (Gebser et al. 2012; Alviano et al. 2017) are able to find solutions for many interesting problems in reasonable time. A way to shed light into this discrepancy is by means of parameterized complexity (Cygan et al. 2015), which conducts more fine-grained complexity analysis in terms of parameters of a problem. For ASP, several results were achieved in this direction (Gottlob, Scarcello, and Sideri 2002; Lons and Truszczynski 2003; Lin and Zhao 2004; Fichte and Szeider 2015), some insights involve even combinations (Lackner and Pfandler 2012; Fichte, Kronegger, and Woltran 2019) of parameters. More recent studies focus on the influence of the parameter treewidth for solving ASP (Jakl, Pichler, and Woltran 2009; Fichte et al. 2017; Fichte and Hecher 2019; Bichler, Morak, and Woltran 2018; Bliem et al. 2020). These works utilize treewidth to solve, e.g., the consistency problem, in polynomial time in the program size, while being superpolynomial only in the treewidth. Recently, it was shown that for normal ASP deciding consistency is expected to be slightly superexponential in the treewidth (Hecher 2020). More concretely, a lower bound was established under the Exponential Time Hypothesis (ETH) (Impagliazzo, Paturi, and Zane 2001), saying that consistency for any normal logic program of treewidth $k$ cannot be decided in time $2^{O(k \log(k))} \cdot poly(n)$, where $n$ is the number of variables (atoms) of the program. This result matches the known upper bound (Fichte and Hecher 2019) and renders the consistency of normal ASP slightly harder than the satisfiability (SAT) of a propositional formula, which under the ETH cannot be decided in time $2^{o(k)} \cdot poly(n)$.

Contributions. We address this result and consider besides treewidth, the size $\ell$ of the largest strongly-connected component (SCC) of the positive dependency graph as parameter.

1. First, we present a treewidth-aware reduction from head-cycle-free ASP to tight ASP. Our reduction takes any HCF program $\Pi$ and creates a tight program, whose treewidth is at most $O(k \cdot \log(\ell))$, where $k$ is the treewidth of $\Pi$ and $\ell$ is the size of the largest SCC of the dependency graph of $\Pi$. In general, the treewidth of the resulting tight program cannot be in $o(k \cdot \log(k))$, unless ETH fails. Our reduction forms a major improvement for the case $\ell \ll k$. Besides, this reduction bijectively preserves answer sets and can be used for counting and enumerating answer sets.

2. Then, we improve known results (Fichte and Hecher 2019; Hecher 2020) for the consistency of head-cycle-free ASP. We define a novel measure $\iota$ for the “level” tightness of pro-
grams that is bounded by both treewidth \( k \) and the largest SCC size \( \ell \) such that \( \ell = 1 \) for tight programs only. Interestingly, there are programs with large cycles (large values of \( \ell \)), where we have \( \ell = 2 \). We present a treewidth-aware reduction, capable of “increasing” tightness at the cost of higher treewidth, which increases up to \( O(k \cdot \log(\ell)) \). Further, we establish an algorithm for consistency, running in time \( 2^{O(k \cdot \log(\ell))} \cdot \text{poly}(n) \).

3. Finally, we show a treewidth-aware reduction that takes any tight logic program \( \Pi \) and creates a propositional formula, whose treewidth is linear in the treewidth of the program. This reduction cannot be significantly improved under ETH. Our result also establishes that for deciding consistency of tight logic programs of bounded treewidth \( k \), one indeed obtains the same runtime as for SAT, namely \( 2^{O(k \cdot \log(\ell))} \cdot \text{poly}(n) \), which is ETH-tight.

Related Work. While the largest SCC size has already been considered (Janhunen 2006), it has not been studied in combination with treewidth. Also programs, where the number of even and/or odd cycles is bounded, have been analyzed (Lin and Zhao 2004), which is orthogonal to the size of the largest cycle or largest SCC size \( \ell \). Indeed, in the worst-case, each component might have an exponential number of cycles in \( \ell \). Further, the literature distinguishes the so-called feedback width (Gottlob, Scarcello, and Sideri 2002), depending on the atoms required to break large SCCs (positive cycles). There are related measures, called smallest backdoor size, where the removal of a set of atoms from the program results in normal or acyclic programs (Fichte and Szeider 2015).

2 Background

We assume familiarity with graph terminology. Given a directed graph \( G = (V, E) \), then, a set \( C \subseteq V \) of vertices of \( G \) is a strongly-connected component (SCC) of \( G \) if \( G \) is free of two distinct vertices \( u, v \) in \( C \) there is a directed path from \( u \) to \( v \) in \( G \). An SCC \( C \) is called non-trivial, if \( |C| > 1 \). A cycle over some vertex \( v \) of \( G \) is a directed path from \( v \) to \( v \).

Answer Set Programming (ASP). We assume familiarity with propositional satisfiability (SAT) and follow standard definitions of ASP (Brewka, Eiter, and Truszczyński 2011). Let \( m, n, a \) be non-negative integers such that \( m \leq n \leq a \), and let \( a_1, \ldots, a_n \) be distinct propositional atoms. Moreover, we refer by literal to an atom or the negation thereof. A (logic) program \( \Pi \) is a set of rules of the form \( a_1 \lor \cdots \lor a_m \leftarrow a_{m+1}, \ldots, a_n \), \(-a_m, \ldots, -a_n\). For a rule \( \rho \), we let \( H_\rho := \{a_1, \ldots, a_m\}, B_\rho^+: = \{a_{m+1}, \ldots, a_n\}, B_\rho^- := \{-a_{m+1}, \ldots, -a_n\} \). We denote the sets of atoms occurring in a rule \( r \) or in a program \( \Pi \) by \( \text{at}(\Pi) := \bigcup_{r \in \Pi} \text{at}(r) \). For a set \( X \subseteq \text{at}(\Pi) \) of atoms, we let \( X^\rho := \{ x \in X \mid a \leftarrow \} \). A program \( \Pi \) is normal, if \( |H_\rho| \leq 1 \) for every \( r \in \Pi \). The (positive) dependency digraph \( D_{\Pi} \) of \( \Pi \) is the directed graph defined on the set of atoms from \( \bigcup_{r \in \Pi} H_\rho \cup B_\rho^+ \cup B_\rho^- \), where there is a directed edge from vertex \( a \) to vertex \( b \) iff there is a rule \( r \in \Pi \) with \( a \in B_\rho^+ \) and \( b \in H_\rho \). A head-cycle of \( D_{\Pi} \) is a cycle containing two distinct atoms \( a, b \in H_\rho \) for some rule \( r \in \Pi \). A program \( \Pi \)

is head-cycle-free (HCF) if \( D_{\Pi} \) contains no head-cycle (Ben-Eliyahu and Dechter 1994) and \( \Pi \) is called tight (Lin and Zhao 2003) if \( D_{\Pi} \) contains no cycle, i.e., \( \Pi \) has no “positive cycle”. The class of tight, normal, and HCF programs is referred to by tight, normal, and HCF ASP, respectively.

An interpretation \( I \) is a set of atoms. \( I \) satisfies a rule \( r \) if \( H_r \cup B_\rho^- \cap I \neq \emptyset \) or \( B_\rho^+ \cap I \neq \emptyset \). \( I \) is a model of \( \Pi \) if it satisfies all rules of \( \Pi \). For brevity, we view propositional formulas as sets of clauses and use the notion of interpretations, models, and satisfiability analogously. Given a set \( A \subseteq \text{at}(\Pi) \) of atoms, a function \( \sigma : \Pi \rightarrow \{0, \ldots, |A| - 1\} \) is called level mapping over \( A \). Given an interpretation \( I \) of a normal program \( \Pi \) and a level mapping \( \sigma \) over \( I \), an atom \( a \in I \) is proven if there is a rule \( r \in \Pi \) proving \( a \) with \( \sigma \), where \( a \in H_r \), and (i) \( B_\rho^+ \subseteq I \), (ii) \( I \cap B_\rho^- = \emptyset \) and \( \Pi \cap (H_r \setminus \{a\}) = \emptyset \), and (iii) \( \sigma(b) < \sigma(a) \) for every \( b \in B_\rho^+ \). Then, \( I \) is an answer set of \( \Pi \) if (i) \( I \) is a model of \( \Pi \) and (ii) \( I \) is proven, i.e., every \( a \in I \) is proven with \( \sigma \). This characterization (Lin and Zhao 2003) vacuously extends to HCF programs and allows for further simplification when considering SCCs of \( D_{\Pi} \) (Janhunen 2006). To this end, we denote for each atom \( a \in \Pi \) the SCC of \( a \) in \( D_{\Pi} \) by \( \text{sc}(a) \). Then, \( \text{condition} (\text{iii}) \) above can be relaxed to \( \sigma(b) < \sigma(a) \) for every \( b \in B_\rho^+ \cap \text{sc}(a) \).

The problem of deciding whether an ASP program has an answer set is called consistency, which is NP-complete for normal, HCF, and tight programs (Marek and Truszczyński 1991; Ben-Eliyahu and Dechter 1994; Lin and Zhao 2003). In general, semantics are defined via the GL-reduct (Gelfond and Lifschitz 1991), where for arbitrary programs the complexity increases to \( \Sigma_2 \)-complete (Eiter and Gottlob 1995).

Example 1. Consider program \( \Pi := \{r_1, \ldots, r_7\} \), where 
\[ 
\begin{align*}
  r_1 := a & \leftarrow d, \\
  r_2 := b & \leftarrow a, \\
  r_3 := b & \leftarrow d, \\
  r_4 := b & \leftarrow e, \\
  r_5 := c & \leftarrow b, \\
  r_6 := d & \leftarrow b, c, \\
  r_7 := e & \leftarrow a \cup v. 
\end{align*}
\]
Observe that \( \Pi \) is head-cycle-free. Figure 1 shows the positive dependency graph \( D_{\Pi} \) consisting of SCCs \( \text{sc}(a) \), \( \text{sc}(f) \), \( \text{sc}(g) \), and \( \text{sc}(a) = \text{sc}(b) = \text{sc}(c) = \text{sc}(d) \). Then, \( I := \{a, b, c, d, e\} \) is an answer set of \( \Pi \), since \( I \) is a model of \( \Pi \) and with level mapping \( \sigma := (e \leftarrow 0, b \leftarrow 0, c \leftarrow 1, d \leftarrow 2, a \leftarrow 3) \), we prove \( e \) by rule \( r_7 \), \( b \) by rule \( r_4 \) since \( e \notin B_\rho^+ \cap \text{sc}(b) \), \( c \) by \( r_5 \), \( d \) by \( r_6 \), and \( a \) by \( r_1 \). Further answer sets are \( \{f\} \) and \( \{g\} \).
Example 2. Figure 2 illustrates a graph $G$ and a TD $T$ of $G$ of width 2, which is also the treewidth of $G$, since vertices $b,c,d$ are completely connected with each other (Kloks 1994).

In order to use TDs, we need dedicated graph representations. The primal graph $G_{II}$ of a program $II$ (Jädl, Pichler, and Woltran 2009) has the atoms of $II$ as vertices and an edge $\{a,b\}$ if there exists a rule $r \in II$ and $a,b \in \text{at}(r)$, and the treewidth of $II$ equals $tw(G_{II})$. Similarly, $G_F$ denotes the primal graph of a formula $F$ and the treewidth of $F$ equals $tw(G_F)$. Let $T = (T, \chi)$ be a TD of primal graph $G_{II}$, and let $t$ be a node of $T$. Then, the bag program $II_t$ contains rules covered by $\chi(t)$, i.e., $II_t := \{ r \mid r \in II, \text{at}(r) \subseteq \chi(t) \}$.

Example 3. Recall program $II$ from Example 1 and observe that graph $G$ of Figure 2 is the primal graph $G_{II}$ of $II$. Further, we have $II_{t_1} = \{ r_1, r_2, r_3 \}$, $II_{t_2} = \{ r_3, r_5, r_6 \}$, $II_{t_3} = \emptyset$, $II_{t_4} = \{ r_7 \}$, and $II_{t_5} = \{ r_4 \}$.

3 Bounding Treewidth and Positive Cycles

Recently, it was shown that under reasonable assumptions, namely the exponential time hypothesis (ETH), the consistency of normal logic programs is strictly superexponential and one cannot significantly improve in the worst case.

Proposition 1 (Lower Bound (Hecher 2020)). Given a normal or HCF logic program $II$, where $k$ is the treewidth of the primal graph of $II$. Then, under ETH one cannot decide consistency of $II$ in time $2^{\omega(k \log(k))} \cdot \text{poly}(|\text{at}(II)|)$.

While according to Proposition 1, we cannot expect to significantly improve the runtime for normal logic programs in the worst case, it still is worth studying the underlying reason that makes the worst case so bad. It is well-known that positive cycles are responsible for the hardness (Lifschitz and Razborov 2006; Janhunen 2006) of computing answer sets of normal logic programs. The particular issue with logic programs $II$ in combination with treewidth and large cycles is that in a TD of $G_{II}$ it might be the case that the cycle spreads across the whole decomposition, i.e., TD bags only contain parts of such cycles, which makes it impossible to view these cycles (and dependencies) as a whole. This is also the reason of the hardness given in Proposition 1 and explains why under bounded treewidth evaluating normal logic programs is harder than evaluating propositional formulas. However, if a given normal program only has positive cycles of length at most 3, and each atom appears in at most one positive cycle, the properties of TDs ensure that the atoms of such positive cycle appear in at least one common bag. Indeed, a cycle of length at most 3 forms a completely connected subgraph and therefore it is guaranteed (Kloks 1994) that the atoms of the cycle are in one common bag of any TD of $G_{II}$.

Example 4. Recall program $II$ of Example 1. Observe that in any TD of $G_{II}$ it is required that there are nodes $t, t'$ with $\chi(t) \subseteq \{ b, c, d \}$ and $\chi(t') \subseteq \{ a, b, d \}$ since a cycle of length 3 in the positive dependency graph $D_1$ (cf. Figure 1) is completely connected in $G_{II}$, cf. Figure 2 (left).

It is known that the size of a TD grows exponentially in the treewidth of the primal graph $G_{II}$.

Bounding Positive Cycles. In the remainder of this work, we assume an HCF logic program $II$, whose treewidth is given by $k = tw(G_{II})$. We let $\ell_{\text{sec}(a)} = 1$ for each atom $a$ be the number of atoms (size) of the SCC of $a$ in $D_{II}$. Further, we let $\ell := \max_{a \in \text{at}(II)} \ell_{\text{sec}(a)}$ be the largest SCC size. This also bounds the lengths of positive cycles. If each atom $a$ appears in at most one positive cycle, we have that $\ell_{\text{sec}(a)}$ is the cycle length of $a$ and then $\ell$ is the length of the largest cycle in $II$. We refer to the class of HCF logic programs, whose largest SCC size is bounded by a parameter $\ell$ by SCC-bounded ASP. Observe that the largest SCC size $\ell$ is orthogonal to treewidth.

Example 5. Consider program $II$ from Example 1. Then, $\ell_{\text{sec}(c)} = 1$, $\ell_{\text{sec}(f)} = 1$, $\ell_{\text{sec}(a)} = 4$, $\ell_{\text{sec}(b)} = 4$, and $\ell = 4$. Assume a program $II'$, whose primal graph equals the dependency graph, which is just one large (positive) cycle. This program has treewidth 2 and one can define a TD of $G_{II'}$, whose bags are constructed along the cycle. However, the largest SCC size $\ell = |\text{at}(II')|$. Conversely, there are programs of large treewidth with no positive cycle.

Bounding sizes of SCCs seems similar to the non-parameterized context, where the consistency of normal logic programs is compiled to a propositional formula (SAT) by a reduction based on level mappings that is applied on an SCC-by-SCC basis (Janhunen 2006). However, this reduction does not preserve the treewidth. On the other hand, while our approach also uses level mappings and proceeds on an SCC-by-SCC basis, the overall evaluation is not SCC-based, since this might completely destroy the treewidth in the worst-case. Instead, the evaluation is guided along a TD.

4 Treewidth-Aware Reductions for

SCC-bounded ASP

Next, we present a treewidth-aware reduction from HCF ASP to tight ASP. More precisely, for an HCF program $II$ with largest SCC size $\ell$, where $k$ is the treewidth of $G_{II}$, the resulting tight program has treewidth $O(k \cdot \log(\ell))$.

Reduction to Tight ASP

The overall construction of the reduction is inspired by the idea of treewidth-aware reductions (Hecher 2020), where in the following, we assume an SCC-bounded program $II$ and a TD $T = (T, \chi)$ of $G_{II}$ such that the construction of the
resulting tight logic program $\Pi'$ is heavily guided along $\mathcal{T}$. In contrast to existing work (Hecher 2020), bounding cycles with the largest SCC size additionally allows to have a “global” level mapping (Janhunen 2006), i.e., we do not have different levels for an atom in different bags. Then, while the overall reduction is still guided along the TD $\mathcal{T}$ in order to only slightly increase treewidth, these global level mappings ensure that the tight program is guaranteed to bijectively preserve all answer sets, as stated in Theorem 1.

Before we discuss the construction in detail, we require auxiliary atoms and notation as follows. In order to guide the evaluation of the provability of an atom $x \in \text{at}(\Pi)$ in a node $t$ in $\mathcal{T}$ along the decomposition $\mathcal{T}$, we use atoms $p^+_t$ and $p^-_t$ to indicate that $x$ was proven in node $t$ (with some rule in $\Pi_t$) and below $t$, respectively. Further, we require level mappings similar to related work (Janhunen 2006), but adapted to SCC-bounded programs. Formally, a level mapping $\sigma : A \to \{0, \ldots, \ell-1\}$ for set of atoms $A \subseteq \text{at}(\Pi)$ is a function mapping each atom $x \in A$ to a level $\sigma(x)$ such that the level does not exceed $\ell_{\text{sec}(x)}$, i.e., $\sigma(x) < \ell_{\text{sec}(x)}$. We use atoms $b_t^i$, called level bits, for $x \in \text{at}(\Pi)$ and $1 \leq j \leq \lfloor \log(\ell_{\text{sec}(x)}) \rfloor$, which are used as bits in order to represent in a level mapping the level of $x$ in binary. To this end, we denote for $x$ and a number $i$ with $0 \leq i < \ell_{\text{sec}(x)}$ as well as a position number $1 \leq j \leq \lfloor \log(\ell_{\text{sec}(x)}) \rfloor$, the $j$-th position of $i$ in binary by $[i]^j$. Then, we let $[x]_i$ be the consistent set of literals over level bits $b_t^i$ that is used to represent level number $i$ for $x$ in binary. More precisely, for each position number $j$, $[x]_i$ contains $b_t^j$ if $[i]^j = 1$ and $-b_t^j$ otherwise, i.e., if $[i]^j = 0$. Finally, we use auxiliary atoms of the form $x \prec_t^i$ to indicate that the level for $x$ represented by $[x]_i$ is indeed smaller than $i > 0$, which is used in the context of node $t$ and a rule $r \in \Pi_t$ for technical reasons. However, we omit $r$ and $t$ in “$\prec^i_t$” if clear from the context.

Example 6. Recall program $\Pi$, level mapping $\sigma$, and largest SCC size $\ell = 4$ from Example 1. For representing $\sigma$ in binary, we require $\lfloor \log(\ell) \rfloor = 2$ bits per atom $a \in \text{at}(\Pi)$ and we assume that bits are ordered from least to most significant bit. So $\sigma(a)^{[0]} = \sigma(a)^{[1]} = 0$, $\sigma(a)^{[2]} = 1$ and $\sigma(a)^{[3]} = 0$. Then, $[\sigma(a)] = \{b_0^1, b_1^0, \overline{b_0^1}, \overline{b_1^0}, [b_0^2, b_1^2, \overline{b_0^2}, \overline{b_1^2}, [b_0^3, b_1^3, \overline{b_0^3}, \overline{b_1^3}]\}$. $d_{\sigma(a)} = \{b_0^1, b_1^0, \overline{b_0^1}, \overline{b_1^0}, [b_0^2, b_1^2, \overline{b_0^2}, \overline{b_1^2}, [b_0^3, b_1^3, \overline{b_0^3}, \overline{b_1^3}]\}$.

Next, we are ready to discuss the treewidth-aware reduction from SCC-bounded ASP to tight ASP, which takes $\Pi$ and $\mathcal{T}$ and creates a tight logic program $\Pi'$. To this end, let $t$ be any node of $\mathcal{T}$. First, truth values for each atom $x \in \chi(t)$ are subject to a guess by Rules (1) and by Rules (2) it is ensured that all rules of $\Pi_t$ are satisfied. Notably, by the definition of TDs, Rules (1) and Rules (2) indeed cover all the atoms of $\Pi$ and all rules of $\Pi$, respectively. Then, the next block of rules consists of Rules (3)–(9) is used for ensuring provability and finally the last block of Rules (10)–(12) is required in order to preserve answer sets, i.e., these rules prevent duplicate answer sets of $\Pi'$ for an answer set of $\Pi$.

For the block of Rules (3)–(9) to ensure provability, we need to guess the level bits for each atom $x$ as given in Rules (3). Rules (4) ensure that we correctly define $x \prec_t^i$, which is the case if there exists a bit $[i]^j$ that is set to 1, but we have $-b_t^j$ and for all larger bits $[i]^j$ that are set to 0 ($j' > j$), we also have $-b_t^{j'}$. Then, for Rules (5) we slightly abuse notation $x \prec_t^i$ for a set $X$, where $X \prec_t^i$ denotes a set of atoms of the form $x \prec_t^i$ for each $x \in X$. Rules (5) make sure that whenever a rule $r \in \Pi$ proves $x$ with the level mapping given by the level bits over atoms in $\chi(t)$, we have provability $p^+_t$ for $x$ in $t$. However, only for the atoms of the positive body $B_t^+$ which are also in the same SCC $C = \text{sec}(x)$ as $x$ we need to check that the levels are smaller than the level of $x$, since by definition of SCCs, there cannot be a positive cycle among atoms of different SCCs. As a result, if there is a rule, where no atom of the positive body is in $C$, satisfying the rule is enough for proving $x$. If provability $p^+_t$ holds, we also have $p^-_t$, by Rules (6) and provability is propagated from node $t'$ to its parent node $t$ by setting $p^-_{t'}$ if $p^-_{t' \prec t}$, as indicated by Rules (7). Finally, whenever an atom $x$ is not present above a node $t$, we require provability $p^-_{t \prec t}$, ensured by Rules (8) and (9).

Preserving answer sets (bijectively): The last block consisting of Rules (10), (11), and (12) makes sure that atoms that are false or not in the answer set of $\Pi'$ get level 0 and that we prohibit levels for an atom $x$ that can be decreased by one without losing provability. This ensures that for each answer set of $\Pi$ we get exactly one answer set of $\Pi'$ and vice versa.

\begin{equation}
\{x\} \leftarrow \quad \text{for each } x \in \chi(t); \text{ see}^1 \quad (1)
\end{equation}

\begin{equation}
\{b_t^i\} \leftarrow \quad \text{for each } x \in \chi(t), \quad 1 \leq j \leq \lfloor \log(\ell_{\text{sec}(x)}) \rfloor; \text{ see}^1 \quad (2)
\end{equation}

\begin{equation}
x \prec_t^i \leftarrow -b_t^i, \overline{B} \quad \text{for each } r \in \Pi_t, x \in H_r, C = scc(x), \quad 1 \leq i < \ell_C, \quad 1 \leq j \leq \lfloor \log(\ell_C) \rfloor, \quad [i]^j = 1, \quad B = \{(b_t^j) \mid j \leq \lfloor \log(\ell_C) \rfloor, \quad [i]^j = 0\} \quad (3)
\end{equation}

\begin{equation}
p_t^i \leftarrow x, [x]_i \quad \text{for each } r \in \Pi_t, x \in H_r, \quad (B_t^+ \cap C \prec_t^i) \quad (4)
\end{equation}

\begin{equation}
p_{t'}^i \leftarrow -x, [x]_i \quad \text{for each } x \in \chi(t), \quad 1 \leq i < \ell_{\text{sec}(x)} \quad (5)
\end{equation}

\begin{equation}
p_{t' \prec t}^i \leftarrow p_t^i \quad \text{for each } x \in \chi(t) \cap \chi(t'), t' \in \text{child}(t) \quad (6)
\end{equation}

\begin{equation}
x \prec_t^i \quad \text{for each } x \in \chi(t) \cap \chi(t'), t' \in \text{child}(t) \quad (7)
\end{equation}

\begin{equation}
x \prec_{t \prec root(T)} \quad \text{for each } x \in \chi(\text{root}(T)) \quad (8)
\end{equation}

\begin{equation}
x \prec_{t \prec root(T)} \quad \text{for each } x \in \chi(t), \quad \text{ see}^1 \quad 1 \leq j \leq \lfloor \log(\ell_{\text{sec}(x)}) \rfloor \quad (9)
\end{equation}

\begin{equation}
x \prec_t^i \quad \text{for each } x \in \chi(t), \quad B_t^+ \cap C = \emptyset \quad (10)
\end{equation}

\begin{equation}
x \prec_t^i \quad \text{for each } x \in \chi(t), \quad B_t^+ \cap C \neq \emptyset \quad (11)
\end{equation}

\begin{equation}
x \prec_{t \prec root(T)} \quad \text{for each } x \in \chi(\text{root}(T)) \quad (12)
\end{equation}

Example 7. Recall program $\Pi$ of Example 1 and TD $\mathcal{T} = (T, \chi)$ of $G_{\Pi}$ as given in Figure 2. Rules (1) and Rules (2) are constructed for each atom $a \in \text{at}(\Pi)$ and for each rule $r \in \Pi$, $a \prec a' \leftarrow$ for a fresh atom $a'$.
respectively. Similarly, Rules (3) are constructed for each of the \( \log(\ell_{\text{sec}(x)}) \) many bits of each atom \( a \in \text{at}(\Pi) \). Rules (4) serve as auxiliary definitions, where for, e.g., atom \( c \) we construct \( c \rightarrow \neg b^1_c, \neg b^2_c, \neg b^3_c, \neg b^4_c \), and \( c \rightarrow \neg b^5_c \). Next, we show Rules (5)–(12) for node \( t_2 \).

No. Rules

(5) \( p^{d_1}_{b_1} \leftarrow b, \{b^1_1, d \leftarrow 1, d, \neg b, \{b^2_1, d \leftarrow 2, d \}ight. \)

(6) \( p^{d_2}_{b_2} \leftarrow b, \{b^3_1, d \leftarrow 3, d \}

(7) \( p^{d_3}_{b_3} \leftarrow c, \{c^1_1, d \leftarrow 1, d \}

(8) \( p^{d_4}_{b_4} \leftarrow d, \{d^1_1, b \leftarrow 1, c \}

(9) \( p^{d_5}_{b_5} \leftarrow e, \{e^1_1, d \leftarrow 1, d \}

(10) \( p^{d_6}_{b_6} \leftarrow f, \{f^1_1, d \leftarrow 1, d \}

(11) \( p^{d_7}_{b_7} \leftarrow \neg d, \{d^1_1, b \leftarrow 1, c \}

(12) \( p^{d_8}_{b_8} \leftarrow \neg c, \{c^1_1, \neg d \leftarrow 1, d \}

Correctness and Treewidth-Awareness. We discuss correctness and treewidth-awareness, leading then to Theorem 1.

Lemma 1 (Correctness). Let \( \Pi \) be an HCF program, where \( k \) is the treewidth of \( \Pi \) and every SCC satisfies \( |C| \leq \ell \). Then, tight program \( \Pi' \) obtained by Rules (1)–(12) on \( \Pi \) and a TD \( T = (T, \chi) \) of \( \Pi \) is correct. Formally, for any answer set \( I \) of \( \Pi \) there is exactly one answer set \( I' \) of \( \Pi' \) (vice versa).

Proof. “\( \Longrightarrow \)”: Let \( I \) be an answer set of \( \Pi \). Then, there exists a unique (Janhunen 2006), minimal \( \ell \) labeling mapping \( \sigma \) proving each \( x \in I \) with \( 0 \leq \sigma(x) < \ell_{\text{sec}(x)} \). Let \( P := \{p^x_{\ell}, \sigma(x) \in \ell_{\text{sec}(x)} \} \) \( \Rightarrow p^x_{\ell} \leftarrow x, \sigma(x), \in \text{at}(I), t \in T \). From this we construct an interpretation \( I' := \{p^x_{\ell} \leftarrow x, \sigma(x), \in \text{at}(I), t \in T \} \). We prove that this \( I' \) is a TD of \( \Pi' \).

Theorem 1 (Removing Cyclicity of SCC-bounded ASP). Let \( \Pi \) be an HCF program, where the treewidth of \( \Pi \) at most \( k \) and every SCC satisfies \( |C| \leq \ell \). Then, there is a tight program \( \Pi' \) with treewidth in \( O(k \cdot \log(\ell)) \) such that for each answer set \( M \) of \( \Pi \) there is exactly one answer set \( M' \) of \( \Pi' \) that is equal to \( M \) over atoms at(\Pi), and vice versa.

Proof. First, we construct a TD \( T = (T, \chi) \) of \( \Pi \) of width below \( 5 \cdot k \cdot (5\text{-approximation}) \), where \( k = tw(\Pi) \), in time \( 2^{O(k \cdot \log(\ell))} \cdot \text{poly}(\text{at}(\Pi)) \). Observe that the reduction consisting of Rules (1)–(12) on \( \Pi \) and \( \Pi' \) runs in time \( O(k \cdot \log(\ell)^2 \cdot (\text{at}(\Pi) + |\Pi|)) \). The claim follows by correctness (Lemma 1) and treewidth-awareness of Lemma 2.

Reduction to Almost Tight ASP--Balancing Treewidth and Tightness Width

Now, we focus on the consistency problem for SCC-bounded ASP, since relaxing the (bijective) preservation of answer sets allows us to further improve our reduction. Intuitively,
with "local" level mappings which provide level numbers only locally for each TD bag, but ensure compatibility among different bags, one might obtain duplicate answer sets. While these local mappings for TD bags were already used (Hecher 2020), applying local mappings for SCC-bounded ASP enables significant improvements which motivate a new measure for (relaxed variants) of tightness for ASP and treewidth.

**Towards Tightness Width and Almost Tightness.** To this end, let $\Pi$ be an SCC-bounded program, $T = (T, \chi)$ be a TD of $G_\Pi$ of width $k$, $t$ be a node of $T$, and $\ell$ be the largest SCC size of $\Pi$. Then, we let $\ell_{t}^{\operatorname{sec}}(x)$ for each atom $x$ of $\Pi$ be the size of the SCC of $x$ restricted to $\chi(t)$ in $D_{\Pi}$, i.e., $\ell_{t}^{\operatorname{sec}}(x) := |\chi(t) \cap \operatorname{sec}(x)|$. Further, we define the local SCC size $\ell_{t}$ for a node $t$ as follows $\ell_{t} := \max_{x \in \chi(t)} \ell_{t}^{\operatorname{sec}}(x)$ and the tightness width $\nu$ by $\nu := \max_{t \in \ell_\Pi} \ell_{t}$. Intuitively, the local SCC sizes are bounded by the bag sizes ($k + 1$) as well as the largest SCC size $\ell$, but can be even significantly smaller, especially if SCCs are spread across $T$ and if TD bags contain parts of many SCCs. This observation motivates a new (relaxed) measure for almost tightness of ASP and treewidth, where even non-tight ASP programs with large cycles are considered almost tight on $T$, as long as $\nu$ is small (constant). We say program $\Pi$ is $\nu$-tight on $T$, i.e., “almost” tight, if $\nu \geq 2$. Notably, if $\nu = 1$, $\Pi$ is tight and vice versa.

**Example 8. Recall program $\Pi$ of Example 1 and TD $T = (T, \chi)$ of $G_\Pi$ of Figure 2. Observe that $\Pi$ is 3-tight on $T$. Consider program $\Pi'$ from Example 5. While $\ell$ is large ($\ell = |\operatorname{at}(\Pi')|$), we have that $\nu = 3$ for any TD of $G_{\Pi'}$ of width 2.**

**Increasing Almost Tightness (Decreasing $\nu$).** Below, we provide a reduction that reduces the tightness width of almost tight programs. To this end, we assume a program $\Pi$ being $\nu$-tight on a TD $T = (T, \chi)$ of $G_\Pi$, whose width $k$ coincides with the treewidth of $G_\Pi$, and a node $t$ of $T$. The reduction indirectly relies on local level mappings $\sigma_{t} : A \to \{0, \ldots, \ell_{t} - 1\}$ for set of atoms $A \subseteq \operatorname{at}(\Pi)$, which is a function mapping each atom $x \in A$ to a level $\sigma_{t}(x)$ such that the level does not exceed $\ell_{t}^{\operatorname{sec}}(x)$, i.e., $\sigma_{t}(x) < \ell_{t}^{\operatorname{sec}}(x)$. However, we require atoms $b_{t,x}^{i}$, called local level bits, for $x \in \chi(t)$ and $1 \leq j \leq \lfloor \log(\ell_{t}^{\operatorname{sec}}(x)) \rfloor$, for representing level $\sigma_{t}(x)$ of $x$ for node $t$ in $\Pi$. Analogously to above, we denote the $j$-th position of $i$ for $t$ in $\Pi$ with $[i]_{j}$, as well as the consistent literals over local level bits $b_{t,x}^{i}$ for representing level $i$ of $x$ for $t$ by $[x]_{i,j}^{\nu}$. As before, we use auxiliary atoms of the form $x \prec_{t} i$ to indicate $\sigma_{t}(x) < i$ for $x \in H_{t}$ with $r \in \Pi$, as well as provability atoms $p_{t}^{\nu}$ and $p_{t}^{\nu'}$. We are ready to discuss the treewidth-aware reduction from program $\Pi$ being $\nu$-tight on $T$ to a program $\Pi'$ that is $\nu'$-tight on a TD $T'$ with $\nu' < \nu$, where $T'$ is constructed as in Lemma 2. To this end, let $C$ be the union of those non-trivial SCCs of $D_{\Pi}$ that shall be eliminated. If $C = \emptyset$, we obtain the program $\Pi$ as result, and if $C$ are all vertices of any non-trivial SCC of $D_{\Pi}$, we obtain a tight program, whose treewidth is bounded by $O(k \cdot \log(i))$. Consequently, if $C$ are the vertices of those non-trivial SCCs that are responsible for large local SCC sizes, one can increase the level of tightness (decrease $\nu$) at the cost of a slight increase of treewidth. The reduction consists of Rules (13)–(23). First, truth values for each atom $x \in \chi(t) \cap C$ are guessed by Rules (13) and by Rules (14) it is ensured that $\Pi_{t}$ is satisfied and that those atoms in the head $H_{t}$ of a rule $r \in \Pi_{t}$ but not in $C$ still appear in the head. The next block of Rules (15)–(18) is used for guessing local level bits for atoms $x \in \chi(t) \cap C$, cf. Rules (15) and defining auxiliary atom $x \prec_{t} i$ by Rules (16). Further, by Rules (17) and (18) it is ensured that the different local level mappings for different nodes are compatible. More concretely, two neighboring nodes of $T$ do not order two atoms of the same SCC differently. Finally, Rules (19)–(23) ensure provability similar to Rules (5)–(9), but only for atoms in $C$ as well as rules, whose heads contain atoms of $C$.

**Treewidth-Awareness and Consequences.** The reduction above allows us to show Lemma 3 and Theorem 2, whose proofs are similar to Lemma 2 and Theorem 1, respectively.

**Lemma 3 (Treewidth-Awareness).** Let $\Pi$ be a program that is $\nu$-tight on a TD $T$ of width $k$. Then, the treewidth of tight program $\Pi'$ obtained by Rules (13)–(23) on $T$, $T'$, and set $C$ of vertices of all non-trivial SCCs of $D_{\Pi}$, is in $O(k \cdot \log(i))$. 

**Theorem 2 (Removing Cyclicity of $\nu$-tight ASP).** Let $\Pi$ be a program being $\nu$-tight on a TD $T$ of width $k$. Then, there is a tight program $\Pi'$ with treewidth in $O(k \cdot \log(i))$ such that the answer sets of $\Pi$ and $\Pi'$ projected to at(\Pi) coincide.

**Reduction to SAT**

Next, we present a treewidth-aware reduction from tight ASP to SAT, which together with the previous reduction allows
us to reduce from SCC-bounded ASP to SAT. While the step from tight ASP to SAT might seem straightforward for the program obtained by one of the reductions above, in general it is not guaranteed that existing reductions, e.g., (Fages 1994; Lin and Zhao 2003; Janhunen 2006), do not cause a significant blowup in the treewidth.

Let $\Pi$ be any given tight logic program and $T = (T, \chi)$ be a tree decomposition of $G_\Pi$. Similar to the reductions from SCC-bounded ASP to tight ASP, we use as variables besides the original atoms of $\Pi$ also auxiliary variables. In order to preserve treewidth, we still need to guide the evaluation of the provability of an atom $x \in at(\Pi)$ in a node $t$ in $T$ along the TD $T$, whereby we use atoms $p^t_1$ and $p^t_2$ to indicate that $x$ was proven in node $t$ and below $t$, respectively. However, we do not need any level mappings, since there is no positive cycle in $\Pi$, but we still guide provability, cf. Clark’s completion (Clark 1977), along TD $T$. Consequently, we construct the following propositional formula, where for each node $t$ of $T$ we add Formulas (24)–(28). Intuitively, Formulas (24) ensure that all rules are satisfied, cf. Rules (2). Formulas (25) and (26) take care that ultimately an atom that is set to true must be proven, similar to Rules (8) and (9). Finally, Formulas (27) and (28) provide the definition for an atom to be proven in a node and below a node, respectively, which is similar to Rules (5)–(7), but without the level mappings.

Preserving answer sets: We obtain exactly one model of the resulting formula for each answer set of $\Pi$. This can be weakened by turning equivalences $(\leftrightarrow)$ into implications $(\rightarrow)$.

$\forall a \in \overline{B}_t \land \forall a \in \overline{B}_t \land \overline{H}_t$ for each $r \in \Pi$,\hspace{1cm}$24$ for each $t' \in \text{child}(t)$, $x \in \chi(t)$.\hspace{1cm}$25$

$x \rightarrow p^{t'}_{\leq t}$ \hspace{1cm}$26$

$x \rightarrow p^\top \land \left( \bigwedge_{r \in \Pi, x \in H_r, a \in B^+_t} \bigwedge_{b \in B^-_t \land \{x\}} \bigwedge_{r \in \Pi, x \in H_r, a \in B^+_t} \bigwedge_{b \in B^-_t \land \{x\}} \right)$\hspace{1cm}for each $r \in \Pi$, $x \in H_r$, $a \in B^+_t$, $b \in B^-_t \land \{x\}$\hspace{1cm}$27$

$p^t_1 \leftrightarrow \bigvee_{r \in \Pi, x \in H_r, a \in B^+_t} \bigvee_{b \in B^-_t \land \{x\}}$\hspace{1cm}for each $x \in \chi(t)$\hspace{1cm}$28$

**Correctness and Treewidth-Awareness.** Conceptually the proofs of Lemmas 4 and 5 proceed similar to the proofs of Lemmas 1 and 2, but without level mappings, respectively.

**Lemma 4 (Correctness).** Let $\Pi$ be a tight logic program, where the treewidth of $G_\Pi$ is at most $k$. Then, the propositional formula $F$ obtained by the reduction above on $T$ and a TD $T$ of primal graph $G_\Pi$, consisting of Formulas (24)–(28), is correct. Formally, for any answer set $I$ of $\Pi$ there is exactly one satisfying assignment of $F$ and vice versa.

**Lemma 5 (Treewidth-Awareness).** Let $\Pi$ be a tight logic program. Then, the treewidth of propositional formula $F$ obtained by the reduction above, consisting of Formulas (24)–(28), by using $\Pi$ and a TD $T$ of $G_\Pi$ of width $k$ is in $O(k)$.\hspace{1cm}$29$

However, we cannot do much better, as shown next.

**Proposition 2 (ETH-Tightness).** Let $\Pi$ be a tight logic program, where the treewidth of $G_\Pi$ is at most $k$. Then, under ETH, one cannot reduce $\Pi$ to propositional formula $F$ in time $2^{o(k \cdot \log(k)) \cdot \text{poly}(|at(\Pi)|)}$ such that $tw(G_F)$ is in $o(k)$.\hspace{1cm}$30$

**Proof.** First, we reduce SAT to tight ASP, i.e., capture all models of a given formula $F$ in a tight program $\Pi$. Thereby $\Pi$ consists of a choice rule for each variable of $F$ and a constraint for each clause. Towards a contradiction assume the contrary of this proposition. Then, we reduce $\Pi$ back to a propositional formula $F'$, running in time $2^{o(k \cdot \log(k)) \cdot \text{poly}(|at(\Pi)|)}$ with $tw(G_{F'})$ being in $o(k)$. Hence, we use an algorithm for SAT (Samer and Szeider 2010) on $F'$ to solve $F'$ with $n$ variables in time $2^{o(k \cdot \log(k)) \cdot \text{poly}(|at(\Pi)|)}$, which contradicts ETH.\hspace{1cm}$31$

Knowing that under ETH tight ASP has about the same complexity for treewidth as SAT, cf. Proposition 2, we can derive the following corollary, which completes Proposition 1.

**Corollary 1.** Let $\Pi$ be any normal logic program, where the treewidth of $G_\Pi$ is at most $k$. Then, under ETH, one cannot reduce $\Pi$ to a tight logic program $\Pi'$ in time $2^{o(k \cdot \log(k)) \cdot \text{poly}(|at(\Pi)|)}$ such that $tw(G_{\Pi'})$ is in $o(k \cdot \log(k))$.\hspace{1cm}$32$

The consistency of a program $\Pi$ that is $\epsilon$-tight on $T$ can be decided in a runtime that is similar to the runtime of SAT for small $\epsilon$, which improves Proposition 1 as follows.

**Theorem 3 (Runtime of $\epsilon$-tight ASP).** Assume a program $\Pi$ that is $\epsilon$-tight on a TD $T$ of width $k$, whose number of nodes is linear in $|at(\Pi)|$. Then, there is an algorithm for deciding the consistency of $\Pi$, running in time $2^{\log(k \cdot \log(\log(k)) \cdot \text{poly}(|at(\Pi)|)}$.\hspace{1cm}$33$

**Proof.** First, we apply the reduction of Section 4 on $\Pi$ and $T$ on the set $C$ of all non-trivial SCCs of $D_\Pi$. This results in a tight program, which is reduced by the reduction of Section 4 to obtain a propositional formula $F$. Both reductions run in time $O(k^2 \cdot \epsilon^2 \cdot \log(\epsilon) \cdot (|at(\Pi)| + |\Pi|))$. Finally, formula $F$, whose treewidth is in $O(k \cdot \log(\log(k))$ by Lemmas 3 and 5, are solved by an algorithm (Samer and Szeider 2010) for SAT in time $2^{\log(k \cdot \log(\log(k)) \cdot \text{poly}(|at(\Pi)|)}$.\hspace{1cm}$34$

Theorem 3 assumes a given TD, efficiently computable by means of heuristics (Abseher, Musliu, and Woltran 2017). Alternatively, one can compute (Bodlaender et al. 2016) A TD of $G_\Pi$ of width below $5 \cdot tw(G_\Pi)$ (5-approximation) that has a number of nodes linear in $|at(\Pi)|$, in time $2^{O(k \cdot \log(\log(k))) \cdot \text{poly}(n)}$.\hspace{1cm}$35$

**5 Conclusion and Future Work**

This paper deals with improving algorithm for deciding consistency of head-cycle-free (HCF) ASP of bounded treewidth. Existing works imply that under the exponential time hypothesis (ETH), one cannot solve an HCF program with $n$ atoms and treewidth $k$ in time $2^{o(k \cdot \log(k)) \cdot \text{poly}(n)}$.\hspace{1cm}$36$

In this work, we also consider the size $\ell$ of the largest SCC of the positive dependency graph, yielding a more precise characterization of the runtime: $2^{O(k \cdot \log(\log(k)) \cdot \text{poly}(n))}$, where $\ell$ is a novel measure bounded by both $k$ and $\ell$ for measuring the tightness of a program ($\epsilon = 1$ for tight programs only). Further, we provide a treewidth-aware reduction from HCF ASP to tight ASP, where the treewidth increases from $k$ to $O(k \cdot \log(\log(k)))$. Finally, under ETH, tight ASP has similar complexity as SAT: There is no reduction from HCF ASP to tight ASP, increasing treewidth from $k$ to only $o(k \cdot \log(k))$.\hspace{1cm}$37$

Currently, we are performing practical analysis of our provided reductions. For future work we suggest to investigate lower bounds for both parameters $k$, $\ell$, or under extensions of ETH like strong ETH (Impagliazzo and Paturi 2001).
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