Disjunctive Answer Set Solvers via Templates

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Abstract

Answer set programming is a declarative programming paradigm oriented towards difficult combinatorial search problems. A fundamental task in answer set programming is to compute stable models, i.e., solutions of logic programs. Answer set solvers are the programs that perform this task. The problem of deciding whether a disjunctive program has a stable model is \( \Sigma_2^p \)-complete. The high complexity of reasoning within disjunctive logic programming is responsible for few solvers capable of dealing with such programs, namely DLV, GNT, CMODELS, CLASP and WASP. In this paper we show that transition systems introduced by Nieuwenhuis, Oliveras, and Tinelli to model and analyze satisfiability solvers can be adapted for disjunctive answer set solvers. Transition systems give a unifying perspective and bring clarity in the description and comparison of solvers. They can be effectively used for analyzing, comparing and proving correctness of search algorithms as well as inspiring new ideas in the design of disjunctive answer set solvers. In this light, we introduce a general template, which accounts for major techniques implemented in disjunctive solvers. We then illustrate how this general template captures solvers DLV, GNT, and CMODELS. We also show how this framework provides a convenient tool for designing new solving algorithms by means of combinations of techniques employed in different solvers.

KEYWORDS: Answer Set Programming, Abstract Solvers

1 Introduction

Answer set programming (Marek and Truszczyński 1999; Niemelä 1999; Baral 2003; Eiter et al. 1997; Gelfond and Lifschitz 1988; Gelfond and Lifschitz 1991) is a declarative programming paradigm oriented towards difficult combinatorial search problems. The idea of answer set programming (ASP) is to represent a given problem
with a logic program, whose answer sets correspond to solutions of the problem (see e.g., Lifschitz 1999). ASP has been applied to solve problems in various areas of science and technology including graph-theoretic problems arising in zoology and linguistics (Brooks et al. 2007), team building problems in container terminal (Ricca et al. 2012), and product configuration tasks (Soiinen and Niemelä 1999). A fundamental task in ASP is to compute stable models of logic programs. Answer set solvers are the programs that perform this task. There were sixteen answer set solvers participating in the recent Fifth Answer Set Programming Competition1.

Gelfond and Lifschitz introduced logic programs with disjunctive rules (Gelfond and Lifschitz 1991). The problem of deciding whether a disjunctive program has a stable model is $\Sigma_2^P$-complete (Eiter and Gottlob 1993). The problem of deciding whether a non-disjunctive program has a stable model is NP-complete. The high complexity of reasoning within disjunctive logic programming stems from two sources: first, there is a potentially exponential number of candidate models, and, second, the hardness of checking whether a candidate model is a stable model of a propositional disjunctive logic program is co-NP-complete. Only five answer set systems can solve disjunctive programs: dlv (Leone et al. 2006), gnt (Janhunen et al. 2006), cmodels (Lierler 2005), clasp (Gebser et al. 2013) and wasp (Alviano et al. 2013).

Several formal approaches have been used to describe and compare search procedures implemented in answer set solvers. These approaches range from a pseudo-code representation of the procedures (Giunchiglia and Maratea 2005; Giunchiglia et al. 2008), to tableau calculi (Gebser and Schaub 2006; Gebser and Schaub 2013), to abstract frameworks via transition systems (Lierler 2008; Lierler 2011; Lierler and Truszczynski 2011). The latter method originates from the work by Nieuwenhuis et al. (2006), where authors propose to use transition systems to describe the Davis-Putnam-Logemann-Loveland (dpll) procedure (Davis et al. 1962). Nieuwenhuis et al. introduce an abstract framework called dpll graph, that captures what states of computation are, and what transitions between states are allowed. Every execution of the dpll procedure corresponds to a path in the dpll graph. Some edges may correspond to unit propagation steps, some to branching, some to backtracking.

Such an abstract way of presenting algorithms simplifies their analysis. This approach has been adapted (Lierler 2011; Lierler and Truszczynski 2011) to describing answer set solvers for non-disjunctive programs including smodels, cmodels, and clasp. This type of graphs has been used to relate algorithms in precise mathematical terms. Indeed, once we represent algorithms via graphs, comparing the graphs translates into studying the relationships of underlying algorithms. More generally, the unifying perspective of transition systems brings clarity in the description and comparison of solvers. Practically, such graph representations may serve as an effective tool for analyzing, comparing, proving correctness of, and reasoning formally

1 https://www.mat.unical.it/aspcomp2014/FrontPage#Participant_Teams
about the underlying search algorithms. It may also inspire new ideas in the design of solvers.

In this paper we present transition systems that suit multiple disjunctive answer set solvers. We define a general framework, a graph template, which accounts for major techniques implemented in disjunctive answer set solvers excluding backjumping and learning. We study formal properties of this template and we use the template to describe GNT, CMODELS and DLV implementing plain backtracking. We then show how a graph template facilitates a design of new solving algorithms by means of combinations of techniques employed in different solvers. For instance, we present a new abstract solver that can be seen as a hybrid between CMODELS and GNT. We also present how different solvers may be compared by means of transition systems. In particular, we illustrate a close relationship between answer set solvers DLV and CMODELS through the related graphs. The fact that proposed framework does not account for backjumping and learning is one of the reasons that prevents us from capturing such advanced disjunctive answer set solvers as CLASP and WASP. It is a direction of future work to investigate how the proposed framework can be adjusted to accommodate these solvers in full generality.

The paper is structured as follows. Section 2 introduces required preliminaries. Section 3 presents a first abstract solver related to CMODELS. Section 4 defines our general template that accounts for techniques implemented in disjunctive solvers, and Section 5 uses this template to define abstract frameworks for disjunctive solvers. Proofs are presented in Section 6. Section 7 discusses related work and concludes with the final remarks.

The current paper builds on the content presented by Brochenin et al. (2014). It enhances the earlier work by introducing notions of a graph template, “propagator conditions”, and “approximating pairs” that allow to more uniformly account for major techniques implemented in disjunctive answer set solvers. Complete proofs of the formal results are also provided.

2 Preliminaries

2.1 Formulas, Logic Programs, and Program’s Completion

Formulas. Atoms are Boolean variables over \{true, false\}. The symbols ⊥ and ⊤ are the false and the true constants, respectively. The letter \(l\) denotes a literal, that is an atom \(a\) or its negation \(¬a\), and \(l\) is the complement of \(l\), i.e., literal \(a\) for \(¬a\) and literal \(¬a\) for \(a\). Propositional formulas are logical expressions defined over atoms and symbols ⊥, ⊤ in usual way. A finite disjunction of literals is a clause. We identify an empty clause with the symbol ⊥. A conjunction (resp. a disjunction) of literals will sometimes be seen as a set, containing each of its literals. Since a clause is identified with a set of its literals, there are no repetition of literals in a clause. A CNF formula is a finite conjunction (alternatively, a set) of clauses. Since a CNF formula is identified with a set of clauses, there are no repetition of clauses in a CNF formula.

For a conjunction (resp. a disjunction) \(D\) of literals, by \(\overline{D}\) we denote the disjunc-
ation (resp. the conjunction) of the complements of the elements of \(D\). For example, 
\[ a \lor \neg b \] 
denotes \(\neg a \land b\), while 
\[ a \land \neg b \] 
denotes \(\neg a \lor b\). For a set \(L\) of literals, by \(L^\lor\) we
denote the disjunction of its elements and \(L^\land\) the conjunction of its elements; by
\(\text{atoms}(L)\) we denote the set of atoms occurring in \(L\). For a set \(N\) of sets of literals by
\(\text{atoms}(N)\) we denote the set of atoms occurring in the elements of \(N\). For example,
\(\text{atoms}([a, \neg b]) = \{a, b\}\) and \(\text{atoms}([\{a\}, \{\neg b\}]) = \{a, b\}\). For a set \(L\) of literals, by \(L^+\) we denote atoms that occur positively in \(L\). For instance, \(\{a, \neg b\}^+ = \{a\}\).

For a set \(X\) of atoms and a set \(L\) of literals, by \(L_{\downarrow X}\) we denote the maximal subset of \(L\) over \(X\). For example, \(\{(a, \neg b, c)\}_{\{a, b\}} = \{a, \neg b\}\).

A (truth) assignment to a set \(X\) of atoms is a function from \(X\) to \{false, true\}. An assignment satisfies a formula \(F\) if \(F\) evaluates to \(true\) under this assignment. We call an assignment that satisfies formula \(F\) a satisfying assignment or a (classical) model for \(F\). If \(F\) evaluates to \(false\) under an assignment, we say that this assignment contradicts \(F\). If \(F\) has no model we say that \(F\) is unsatisfiable.

For sets \(X\) and \(Y\) of atoms such that \(X \subseteq Y\), we identify \(X\) with an assignment to \(Y\) as follows: if \(a \in X\) then \(a\) maps to \(true\), while if \(a \in Y \setminus X\) then \(a\) maps to \(false\). We also identify a consistent set \(L\) of literals (i.e., a set that does not contain both a literal and its complement) with an assignment to \(\text{atoms}(L)\) as follows: if \(a \in L\) then \(a\) maps to \(true\), while if \(\neg a \in L\) then \(a\) maps to \(false\). The set \(M\) is a complete set of literals over the set of atoms \(X\) if \(\text{atoms}(M) = X\); hence a consistent and complete set of literals over \(X\) represents an assignment to \(X\).

Logic Programs. A head is a (possibly empty) disjunction of atoms. A body is an
expression of the form
\[
a_1, \ldots, a_j, \text{not } a_{j+1}, \ldots, \text{not } a_k
\]  
(1)

where \(a_1, \ldots, a_k\) are atoms, and \text{not} is the negation-as-failure operator. We identify
body (1) with the following conjunction of literals
\[
a_1 \land \ldots \land a_j \land \neg a_{j+1} \land \ldots \land \neg a_k.
\]

Expressions \(a_1, \ldots, a_j\) and \text{not} \(a_{j+1}, \ldots, \text{not} a_k\) are called positive and negative parts
of the body, respectively. Recall that we sometimes view a conjunction of literals as
a set containing all of its literals. Thus, given body \(B\) we may write an expression
\(b \in B\), which means that atom \(b\) occurs in the positive part of the body. Similarly,
an expression \(\neg b \in B\) means that the atom \(b\) (or, in other words, expression \text{not} \(b\))
occur s in the negative part of the body.

A disjunctive rule is an expression of the form \(A \leftarrow B\), where \(A\) is a head and \(B\) is
a body. If \(A\) is empty we drop it from the expression. A disjunctive logic program is
a finite set of disjunctive rules. We call a rule non-disjunctive if its head contains no
more than one atom. A program is non-disjunctive if it consists of non-disjunctive
rules. By \(\text{atoms}(H)\) we denote the set of atoms occurring in a logic program \(H\). If
we understand \(A \leftarrow B\) as a classical logic implication, we can see any rule \(A \leftarrow B\)
as logically equivalent to clause \(A \lor \neg B\) (if \(A\) is an empty clause then we view the
rule as the clause \(\neg B\)). This allows us to view a program \(H\) as a CNF formula when
useful. Conversely, we identify CNF formulas with logic programs: syntactically,
every clause $C$ in a given formula is seen as a rule $\leftarrow C$. For instance $a_1 \lor \neg a_2$ is seen as a rule $\leftarrow \neg a_1, a_2$.

The presented definition of a logic program accounts for propositional programs only. Indeed, all modern disjunctive answer set solvers consider propositional programs only. In practice, answer set programmers devise programs with variables. Software systems called grounders (Syrjänen 2001; Perri et al. 2007) are used to take a logic program with variables as its input and produce a propositional program as its output so that the resulting propositional program has the same answer sets as the input program.

**Reduct and Supporting Rules.** In the following definition we write rules in the form $A \leftarrow B_1, B_2$ where $B_1$ denotes the positive part of the body, whereas $B_2$ denotes the negative part of the body. The reduct $\Pi^X$ of a disjunctive program $\Pi$ with respect to a set $X$ of atoms is obtained from $\Pi$ by deleting each rule $A \leftarrow B_1, B_2$ such that $X \cap \text{atoms}(B_2) \neq \emptyset$ and replacing each remaining rule $A \leftarrow B_1, B_2$ with $A \leftarrow B_1$. A set $X$ of atoms is an answer set of a program $\Pi$ if $X$ is minimal among the sets of atoms that satisfy $\Pi^X$.

For a program $\Pi$, an atom $a$, and a set $L$ of literals, we call any rule $A \lor a \leftarrow B$ in $\Pi$ a supporting rule for $a$ with respect to $L$ when $L \cap (\overline{B} \cup A) = \emptyset$.

A consistent and complete set $L$ of literals over $\text{atoms}(\Pi)$ is

1. a classical model of $\Pi$ if $L$ satisfies every rule in $\Pi$;
2. a supported model of $\Pi$ if $L$ is a classical model of $\Pi$ and for every atom $a \in L^+$ there is a supporting rule for $a$ with respect to $L$;
3. a stable model of program $\Pi$ if $L^+$ is an answer set of $\Pi$.

**Completion.** The completion $\text{comp}(\Pi)$ of a program $\Pi$ is the formula that consists of $\Pi$ and the formulas

$$\{ \neg a \lor \bigvee_{A \lor a \leftarrow B \in \Pi} (B \land \overline{A}) \mid a \in \text{atoms}(\Pi) \}.$$  

This formula has the property that any stable model of $\Pi$ is a classical model of $\text{comp}(\Pi)$. The converse does not hold in general.

For a program $\Pi$ and a consistent set $L$ of literals over $\text{atoms}(\Pi)$, a set $X$ of atoms over $\text{atoms}(\Pi)$ is said to be unfounded (Leone et al. 1997) on $L$ with respect to the program $\Pi$ when for each atom $a \in X$ and each rule $A \leftarrow B \in \Pi$ such that $a \in A$, either of the following conditions hold

1. $L \cap \overline{B} \neq \emptyset$,
2. $X \cap B \neq \emptyset$, or
3. $(A \setminus X) \cap L \neq \emptyset$.

We restate Theorem 4.6 from Leone et al. (1997) that relates the notions of unfounded set and stable model.

**Theorem 1**

For a program $\Pi$ and a consistent and complete set $L$ of literals over $\text{atoms}(\Pi)$, $L$
over X dpll set solvers are based on variations of the cal models of a propositional formula. Most satisfiability and non-disjunctive answer is a well-known method that exhaustively explores sets of literals to generate classi-

The Davis–Putnam–Logemann–Loveland (dpll) proposed by Nieuwenhuis et al. (2006), which is an alternative to common dpll track search-based algorithm. We now review the abstract transition system for dpll answer set solvers.

This theorem is crucial for understanding key computational ideas behind modern answer set solvers.

2.2 Abstract dpll

The Davis–Putnam–Logemann–Loveland (dpll) algorithm from Davis et al. (1962) is a well-known method that exhaustively explores sets of literals to generate classical models of a propositional formula. Most satisfiability and non-disjunctive answer set solvers are based on variations of the dpll procedure that is a classical back-

track search-based algorithm. We now review the abstract transition system for dpll proposed by Nieuwenhuis et al. (2006), which is an alternative to common pseudo-code descriptions of backtrack search-based algorithms. For our purposes it is convenient to state dpll as the procedure applied to a logic program in order to find its classical models.

For a set X of atoms, a record relative to X is a string L composed of literals over X or the symbol ⊥ so that there are no repetitions, and some literals l may be annotated as l̅. The annotated literals are called decision literals. Figure 1 presents the set of all records relative to the singleton set {a}. We say that a record L is inconsistent if it contains both a literal l and its complement l̅, or if it contains ⊥, and consistent otherwise. For instance, only five records in Figure 1, namely ∅, a, ¬a, a̅ and ¬a̅, are consistent. We will sometime view a record as the set containing all its elements disregarding their annotations. For example, a record b̅ ¬a is identified with the set {¬a, b}. A basic state relative to X is either

1. a record relative to X,
2. Ok(L) where L is a record relative to X, or
3. the distinguished state Failstate.

Each program Π determines its dpll graph DPΠ. The set of nodes of DPΠ consists of the basic states relative to atoms(Π). A node in the graph is terminal if no edge originates from it. The state ∅ is called initial. The edges of the graph DPΠ are specified by the transition rules presented in Figure 2.

Intuitively, every state of the dpll graph represents some hypothetical state of the dpll computation whereas a path in the graph is a description of a process of search for a classical model of a given program. The rule Unit asserts that we can add a literal that is a logical consequence of our previous decisions and the

Fig. 1. Records relative to {a}.
Conclude: \( L \implies \text{Failstate} \) if \( \{ \begin{align*} & L \text{ is inconsistent and} \\ & L \text{ contains no decision literals} \end{align*} \)  

Backtrack: \( L \cup L' \implies LI \) if \( \{ \begin{align*} & LI \cup L' \text{ is inconsistent and} \\ & L' \text{ contains no decision literals} \end{align*} \)  

Unit: \( L \implies LI \) if \( \{ \begin{align*} & l \text{ does not occur in } L \text{ and} \\ & \text{a rule in } II \text{ is equivalent to } C \lor l \text{ and} \\ & \text{all the literals of } C \text{ occur in } L \end{align*} \)  

Decide: \( L \implies L \cup l \) if \( \{ \begin{align*} & L \text{ is consistent and} \\ & \text{neither } l \text{ nor } l \text{ occur in } L \end{align*} \)  

Success: \( L \implies \text{Ok}(L) \) if no other rule applies

Fig. 2. Transitions of the graph \( DP_{II} \).

given program. The rule Decide asserts that we make an arbitrary decision to add a literal or, in other words, to assign a value to an atom. Since this decision is arbitrary, we are allowed to backtrack at a later point. The rule Backtrack asserts that the present state of computation is inconsistent but can be fixed: at some point in the past we added a decision literal whose value we can now reverse. The rule Conclude asserts that the current state of computation has failed and cannot be fixed. The rule Success asserts that the current state of computation corresponds to a successful outcome.

We say that a graph \( G \) checks a set \( N \) of sets of literals when all the following conditions hold:

1. \( G \) is finite and acyclic;
2. Any terminal state in \( G \) is either \text{Failstate} or of the form \text{Ok}(L);
3. If a state \text{Ok}(L) is reachable from the initial state in \( G \) then \( L|_{\text{atoms}(N)} \in N \);
4. \text{Failstate} is reachable from the initial state in \( G \) if and only if \( N \) is empty.

Proposition 1

For any program \( II \), the graph \( DP_{II} \) checks the classical models of \( II \).

Thus, to decide the satisfiability of a program \( II \) it is enough to find a path leading from node \( \emptyset \) to a terminal node. If it is \text{Failstate}, then \( II \) has no classical models. Otherwise, \( II \) has classical models. For instance, let \( II_1 \) be

\( \leftarrow \text{not } a, \text{not } b \)
\( \leftarrow a, \text{not } c. \)

Figure 3 presents two paths in \( DP_{II_1} \) from the node \( \emptyset \) to the node \( \text{Ok}(a \cup c \cup b) \). Every edge is annotated on the left by the name of the transition rule that gives rise to this edge in \( DP_{II_1} \). The node \( \text{Ok}(a \cup c \cup b) \) is terminal. Thus, Proposition 1 asserts that \( II_1 \) is satisfiable and \( \{a, c, b\} \) is a classical model of \( II_1 \).

A path in the graph \( DP_{II} \) is a description of a process of search for a classical
model of a program $\Pi$. The process is captured via applications of transition rules. Therefore, we can characterize the algorithm of a solver that utilizes the transition rules of $DP_\Pi$ by describing a strategy for choosing a path. A strategy can be based on assigning priorities to transition rules of $DP_\Pi$ so that a solver never applies a rule in a node if a rule with higher priority is applicable to the same node. The dpll procedure is captured by the priorities ordered as we stated rules in Figure 2. For instance, transition rule Conclude has the highest priority. In Figure 3, the path on the left complies with the dpll priorities: Thus, it corresponds to an execution of the dpll procedure. The path on the right does not: it uses Decide when Unit is applicable. The proof of Proposition 1 follows the lines of the proof of Theorem 2.13 in Nieuwenhuis et al. (2006).

Abstract Answer Set Solver for Non-disjunctive Programs. Lierler (2011) illustrated that extending $DP_\Pi$ by a transition rule

\begin{align*}
\text{Unfounded} & : & L \Rightarrow L \neg a & \text{if} \quad \begin{cases}
\neg a \text{ does not occur in } L \\
L \text{ is consistent and } \\
\text{there is a set } X \text{ of atoms containing } a \text{ such that } \\
X \text{ is unfounded on } L \text{ w.r.t. } II
\end{cases}
\end{align*}

captures a backtrack-search procedure for finding answer sets of non-disjunctive programs. Many answer set solvers for such programs can be seen as extensions of this procedure (Lierler and Truszczynski 2011).

3 A Two-Layer Abstract Solver

The problem of deciding whether a disjunctive program has a stable model is $\Sigma_2^P$-complete (Eiter and Gottlob 1993). This translates into the following: (i) there is an exponential number of possible candidate models, and (ii) the problem of deciding whether a candidate model is an answer set of a disjunctive logic program is co-NP-complete. The latter condition differentiates algorithms of answer set solvers for disjunctive programs from the procedures for non-disjunctive programs. Indeed, the problem of deciding whether a candidate model is an answer set of a non-disjunctive program is tractable.
A common architecture of a disjunctive answer set solver is composed of two layers corresponding to the two above conditions: a generate layer and a test layer, each typically based on DPLL-like procedures. In particular:

- The generate layer is used to obtain a set of candidates that are potentially stable models.
- The test layer is used to verify whether a candidate (produced by the generate layer) is a stable model of the given program.

We now proceed to present a graph $DP^2_{g,t}(\Pi)$ that captures such two-layer architecture. It is based on instances of the DPLL procedure for both its generating task and its testing task. We then illustrate how the $DP^2_{g,t}(\Pi)$ transition system can be used to capture the disjunctive answer set solver cmodels in its basic form.

### 3.1 A Two-Layer Abstract Solver via DPLL

We start by extending the notion of a basic state to accommodate for generate and test layers. We call symbols $L$ and $R$ labels. A state relative to sets $X$ and $X'$ of atoms is either

1. a pair $(L,R)_s$, where $L$ and $R$ are records relative to $X$ and $X'$, respectively, and $s$ is a label (either symbol $L$ or $R$),
2. $Ok(L)$, where $L$ is a record relative to $X$, or
3. the distinguished state $\text{Failstate}$.

We say that a set $M$ of literals covers a program $\Pi$ if $\text{atoms}(\Pi) \subseteq \text{atoms}(M)$. We say that a function $g$ from a program to another program is a generating (program) function if for any program $\Pi$, $\text{atoms}(\Pi) \subseteq \text{atoms}(g(\Pi))$. We call a function from a program $\Pi$ and a consistent set $M$ of literals covering $\Pi$ a witness (program) function. Intuitively, a program $\Pi'$ resulting from a witness function is a witness (program) with respect to $\Pi$ and $M$. For a program $\Pi$ and a witness function $t$, by $\text{atoms}(t,\Pi,X)$ we denote the union of $\text{atoms}(t(\Pi,L))$ for all possible consistent and complete sets $L$ of literals over $X$.

We are now ready to define a graph $DP^2_{g,t}(\Pi)$ for a generating function $g$, a witness function $t$ and a program $\Pi$. The set of nodes of $DP^2_{g,t}(\Pi)$ consists of the states relative to sets $\text{atoms}(g(\Pi))$ and $\text{atoms}(t,\Pi,\text{atoms}(g(\Pi)))$. The state $(\emptyset,\emptyset)_L$ is called initial. The edges of the graph $DP^2_{g,t}(\Pi)$ are specified by the transition rules presented in Figure 4. The graph $DP^2_{g,t}(\Pi)$ can be used for deciding whether a program $g(\Pi)$ has a classical model $M$ such that the witness $t(\Pi,M)$ is unsatisfiable.

**Proposition 2**

For any generating function $g$, any witness function $t$ and any program $\Pi$, the graph $DP^2_{g,t}(\Pi)$ checks the classical models $M$ of $g(\Pi)$ such that $t(\Pi,M)$ is unsatisfiable.
Informal Account of the Two-Layer Abstract Solver. Each of the rules of the graph $DP_{g,t}^2(II)$ is placed into one of the three groups Left, Right, and Crossing. The left-rules of $DP_{g,t}^2(II)$ capture the generate layer that applies the DPLL procedure to the program $g(II)$ produced by the generating function. The right-rules of $DP_{g,t}^2(II)$ capture the test layer that applies the DPLL procedure to the computed witness program. The label $L$ (resp. $R$) suggests that currently the computation is within the generate (resp. test) layer. The left-hand-side $L$ (resp. right-hand-side $R$) of the state $(L, R)_L$ records the computation state due to the generate (resp. test) layer. The crossing rules form a bridge between the two layers.

It turns out that the left-rules no longer apply to a state of the form $(L, R)_L$ only when $L$ is a classical model of $g(II)$. Thus, when a classical model $L$ of $g(II)$

Fig. 4. The transition rules of the graph $DP_{g,t}^2(II)$. 

**Left-rules**

*Conclude*$_L$ $(L, \emptyset)_L \implies \text{Failstate}$ if

$\begin{align*}
L \text{ is inconsistent and} \\
L \text{ contains no decision literal}
\end{align*}$

*Backtrack*$_L$ $(L \Delta L', \emptyset)_L \implies (L', \emptyset)_L$ if

$\begin{align*}
L \text{ is inconsistent and} \\
L' \text{ contains no decision literal}
\end{align*}$

*Unit*$_L$ $(L, \emptyset)_L \implies (L, \emptyset)_L$ if

$\begin{align*}
l \text{ is a literal over atoms } \text{ and} \\
\text{ l does not occur in } L \\
\text{ a rule in } g(II) \text{ is equivalent to } C \lor l \text{ and} \\
\text{ all the literals of } \overline{C} \text{ occur in } L
\end{align*}$

*Decide*$_L$ $(L, \emptyset)_L \implies (L \Delta l, \emptyset)_L$ if

$\begin{align*}
L \text{ is consistent and} \\
l \text{ is a literal over atoms } \text{ and} \\
\text{ neither } l \text{ nor } \overline{l} \text{ occur in } L
\end{align*}$

**Crossing-rule** $LR$

*Cross*$_{LR}$ $(L, \emptyset)_L \implies (L, \emptyset)_R$ if no left-rule applies

**Right-rules**

*Conclude*$_R$ $(L, R)_R \implies \text{Ok}(L)$ if

$\begin{align*}
R \text{ is inconsistent and} \\
R \text{ contains no decision literal}
\end{align*}$

*Backtrack*$_R$ $(L, R \Delta R')_R \implies (L, R')_R$ if

$\begin{align*}
R \text{ is inconsistent and} \\
R' \text{ contains no decision literal}
\end{align*}$

*Unit*$_R$ $(L, R)_R \implies (L, R)_R$ if

$\begin{align*}
l \text{ is a literal over atoms } \text{ and} \\
\text{ l does not occur in } R \\
\text{ a rule in } t(II, L) \text{ is equivalent to } C \lor l \text{ and} \\
\text{ all the literals of } \overline{C} \text{ occur in } L
\end{align*}$

*Decide*$_R$ $(L, R)_R \implies (L, R \Delta l)_R$ if

$\begin{align*}
R \text{ is consistent and} \\
l \text{ is a literal over atoms } \text{ and} \\
\text{ neither } l \text{ nor } \overline{l} \text{ occur in } R
\end{align*}$

Crossing-rules $RL$

*Conclude*$_{LR}$ $(L, R)_R \implies \text{Failstate}$ if no right-rule applies and

$\begin{align*}
L \text{ contains no decision literal}
\end{align*}$

*Backtrack*$_{LR}$ $(L \Delta l', R)_R \implies (L, \emptyset)_L$ if no right-rule applies and

$\begin{align*}
L' \text{ contains no decision literal}
\end{align*}$
is found, then the \texttt{Cross}_{\text{LR}} is used and a witness program with respect to \( L \) is computed. If no classical model is found for the witness program, then \texttt{Conclude}_{\text{R}} rule applies, which brings us to a terminal state \( \text{Ok}(L) \), suggesting that \( L \) represents a solution to a given search problem. It turns out that no right-rules applies in a state of the form \( (L, R)_{\text{R}} \) only when \( R \) is a classical model for the witness program. Thus, the set \( L \) of literals is not such that \( t(\Pi, M) \) is unsatisfiable and the \texttt{dpll} procedure of the generate layer, embodied by the left-rules, proceeds with the search, after backtracking through \texttt{Backtrack}_{\text{R_L}}. In the case when \texttt{Backtrack}_{\text{R_L}} cannot be applied, it follows that no other candidate can be found by the generate layer, so the transition \texttt{Conclude}_{\text{R_L}} leading to \texttt{Failstate} is the only available one from such a state.

### 3.2 Abstract basic cmodes

We now relate the graph \( DP^2_{g,t}(\Pi) \) to the procedure \texttt{dp-assat-proc} from Lierler (2005). This procedure forms the basis of the answer set solver \texttt{cmodels}. Yet, it does not account for backjumping and learning techniques, implemented in \texttt{cmodels}.

Given a disjunctive program \( \Pi \), the answer set solver \texttt{cmodels} starts its computation by computing a CNF formula \( g^C(\Pi) \) that corresponds to the clausified program completion of \( \Pi \). The \texttt{dpll} procedure is then applied to \( g^C(\Pi) \). The test layer of the \texttt{cmodels} computation relies on the programs produced by a witness program function called \( t^C \) that intuitively tests minimality of found models of completion.

To be complete in our presentation, we now review the details of \( g^C \) and \( t^C \) functions (Lierler 2010). To construct \( g^C(\Pi) \), \texttt{cmodels} introduces an auxiliary atom \( \alpha_B \) for every body \( B \) occurring in \( \Pi \). The atom \( \alpha_B \) is an explicit definition for \( B \), it is true if and only if \( B \) is true. Also every disjunctive rule gives rise to as many auxiliary variables as there are atoms in the head of the rule: for a disjunctive rule \( A \leftarrow B \) and every atom \( a \in A \), an auxiliary atom \( \alpha_{a,B} \) is equivalent to a conjunction \( B \land \tilde{A} \), where \( \tilde{A} \) is \( (A \setminus \{a\})^\vee \). Formulas (3) and (4) present the definitions of \( g^C \) and \( t^C \) for a program \( \Pi \). The first four lines of the definition of the CNF formula \( g^C(\Pi) \) concern clausification of the introduced explicit definitions, namely \( \alpha_B \) and \( \alpha_{a,B} \). The last two lines encode clausified completion with the use of \( \alpha_B \) and \( \alpha_{a,B} \).

\[
g^C(\Pi) = \begin{cases} 
\alpha_B \lor \overline{B} & | B \in \text{Bodies}(\Pi) \\
\neg \alpha_B \lor a & | B \in \text{Bodies}(\Pi), a \in B \\
\alpha_{a,B} \lor \neg \alpha_B \lor A & | A \lor a \leftarrow B \in \Pi \\
\neg \alpha_{a,B} \lor a & | A \lor a \leftarrow B \in \Pi, b \in \overline{A} \cup \{\alpha_B\} \\
\neg \alpha_B \lor A & | A \leftarrow B \in \Pi \\
\neg a \bigvee_{a \in \text{Bodies}(\Pi)} \alpha_{a,B} \bigvee_{A \lor a \leftarrow B \in \Pi} \alpha_{a,B} 
\end{cases} \tag{3}
\]
\[ t^C(\Pi, M) = (M^+_{\text{atom}(\Pi)}) \} \cup \{ \neg a \mid \neg a \in M_{\text{atom}(\Pi)} \} \cup \{ B \lor A \mid A \leftarrow B \in \Pi^{M^+}, B \subseteq M \}, \]

Intuitively, CMODELS uses the program \( g^C(\Pi) \) as an approximation of \( \Pi \) during the generate-layer computation. Indeed, any stable model of \( \Pi \) is also a classical model of \( g^C(\Pi) \). The converse does not always hold. Thus, classical models of \( g^C(\Pi) \) must be checked. For a classical model \( M \) of \( g^C(\Pi) \), a program produced by \( t^C(\Pi, M) \) has no classical models iff \( M \) is a stable model of \( \Pi \). In fact, any model \( N \) of \( t^C(\Pi, M) \) is such that it satisfies the reduct \( \Pi^{M^+} \), while \( N^+ \subseteq M^+_{\text{atom}(\Pi)} \). In such case, \( M^+_{\text{atom}(\Pi)} \) is not an answer set of \( \Pi \) by definition and, consequently, \( M \) is not a stable model of \( \Pi \).

By \( DP^2_\Pi \) we denote the graph \( DP^2_{g^C, t^C}(\Pi) \). Proposition 3 below illustrates that the graph \( DP^2_\Pi \) can be used for deciding whether a given program \( \Pi \) has a stable model, similarly as the graph \( DP_\Pi \) can be used for deciding whether \( \Pi \) has a classical model.

**Proposition 3**

For any program \( \Pi \), the graph \( DP^2_\Pi \) checks the stable models of \( \Pi \).

The graph \( DP^2_\Pi \) captures the search procedure of DP-ASSAT-PROC of CMODELS. The DP-ASSAT-PROC algorithm follows the priorities on its transition rules as they are ordered in Figure 4. We often use this convention when describing other procedures in the sequel.

### 4 Graph Templates

The differences in design choices of disjunctive answer set solvers obscure the understanding of their similarities. In Brochenin et al. (2014), transition systems exemplified by the graph \( DP^2_\Pi \) were used to capture several disjunctive solvers, namely, CMODELS, GNT and DLV implementing backtracking. The transitions systems made the similarities that these solvers share explicit. For example, all solvers are based on a two-layer approach in the spirit of the DP-ASSAT-PROC algorithm. In this work, we make an additional move towards a unifying framework for capturing two-layer methods. We introduce a graph template that we then use to encompass disjunctive solvers CMODELS, GNT and DLV.

#### 4.1 A Single Layer Graph Template

In the next section we will define a graph template suitable for capturing two-layer computation of disjunctive answer set solvers. As a step in this direction, we describe here a simpler graph template that can be used to capture the DPLL procedure by encapsulating the DPLL graph. We also show that this template can encapsulate a graph capturing the computation underlying the algorithm of answer set solver SMODELS for non-disjunctive programs.
l ∈ UnitPropagate(Π, L)
    if \( l \) does not occur in \( L \) and
    a rule in \( \Pi \) that is equivalent to \( C \lor l \) and
    all the literals of \( \overline{C} \) occur in \( L \)

\neg a ∈ AllRulesCancelled(Π, L)
    if \( \neg a \) does not occur in \( L \) and
    there is no rule in \( \Pi \) supporting \( a \) with respect to \( L \)

l ∈ BackchainTrue(Π, L)
    if \( \begin{cases} 
        l \text{ does not occur in } L \\
        \text{there is a rule } A \lor a \leftarrow B \text{ in } \Pi \\
        \text{so that (i) } a \in L, \text{ and (ii) either } \overline{A} \lor l \text{ or } l \in \overline{B} \text{ and,} \\
        \text{(iii) no other rule in } \Pi \text{ is supporting } a \text{ with respect to } L 
    \end{cases} \)

\neg a ∈ Unfounded(Π, L)
    if \( \begin{cases} 
        \neg a \text{ does not occur in } L \\
        L \text{ is consistent and} \\
        \text{there is a set } X \text{ of atoms containing } a \text{ such that} \\
        X \text{ is unfounded on } L \text{ with respect to } \Pi 
    \end{cases} \)

Fig. 5. Propagator conditions.

Template. A function from a program \( \Pi \) and a set of literals over \( \text{atoms}(\Pi) \) to a set of literals over \( \text{atoms}(\Pi) \) is called a propagator condition or, shortly, \( p \)-condition. Figure 5 presents four \( p \)-conditions, namely, UnitPropagate, AllRulesCancelled, BackchainTrue, and Unfounded. For a set \( \mathcal{P} \) of \( p \)-conditions, a program \( \Pi \) and a set \( M \) of literals, by \( \mathcal{P}(\Pi, M) \) we denote the set of literals \( \bigcup_{\mathcal{p} \in \mathcal{P}} \mathcal{p}(\Pi, M) \). Intuitively, if each image through a \( p \)-condition is a set of possible outcomes, this set represents the union of the possible outcomes through \( \mathcal{P} \).

Definition 1
Given a a program \( \Pi \) and a set \( \mathcal{P} \) of \( p \)-conditions, a DPLL graph template \( DPT_{\mathcal{P}, \Pi} \) is a graph of which nodes are the basic states relative to \( \text{atoms}(\Pi) \) and edges are specified by the transition rules Conclude, Backtrack, Decide, and Success presented in Figure 2 and the transition rule

\[
\text{Propagate } \quad L \quad \Rightarrow Ll \quad \text{if} \quad l \in \mathcal{P}(\Pi, L). \tag{5}
\]

For instance, the instantiation \( DPT_{\{\text{UnitPropagate}\}, \Pi} \) of the DPLL graph template results in the DPLL graph \( DP_{\Pi} \). Indeed, by definition these graphs share the same nodes as well as their rules Conclude, Backtrack, Decide, and Success coincide. Then, one can see that \( l \in \text{UnitPropagate}(\Pi, L) \) if and only if the transition rule Unit in \( DP_{\Pi} \) is applicable in \( L \) and supports the transition to a state \( Li \), which shows that the Unit rule and the Propagate rule coincide when \( \mathcal{P} = \{\text{UnitPropagate}\} \).

Instantiation. We call types the elements of the set \( T = \{\text{cla, sup, sta}\} \). In the following, by cla-model, sup-model and sta-model we denote classical, supported, and stable models, respectively. We also use letter \( w \) to denote a variable over set \( T \) of types. We say that a set \( \mathcal{P} \) of \( p \)-conditions is \( w \)-sound if for any program \( \Pi \), for
any set $M$ of literals, and for any $w$-model $M_1$ of $\Pi$ such that $M \subseteq M_1$, it also holds that $\mathcal{P}(\Pi, M) \subseteq M_1$. Note that any cla-sound set of p-conditions is sup-sound, and any sup-sound set of p-conditions is sta-sound. We say that a set $\mathcal{P}$ of p-conditions is $w$-complete when for any program $\Pi$ and any consistent and complete set $M$ of literals over $\text{atoms}(\Pi)$, set $M$ is a $w$-model of $\Pi$ if and only if $\mathcal{P}(\Pi, M) = \emptyset$. For a type $w$, we say that a set $\mathcal{P}$ of p-conditions is $w$-enforcing if $\mathcal{P}$ is both $w$-sound and $w$-complete.

Next theorem summarizes properties of several sets of p-conditions:

\begin{align*}
\text{up} &= \{\text{UnitPropagate}\} \\
\text{sd} &= \{\text{UnitPropagate}, \text{AllRulesCancelled}, \text{BackchainTrue}\} \\
\text{sm} &= \{\text{UnitPropagate}, \text{AllRulesCancelled}, \text{BackchainTrue}, \text{Unfounded}\}
\end{align*}

**Theorem 2**
The following statements hold:

1. The set $\text{up}$ is cla-enforcing;
2. All the subsets of $\text{sd}$ that contain $\{\text{UnitPropagate}, \text{AllRulesCancelled}\}$ are sup-enforcing; and
3. All the subsets of $\text{sm}$ that contain $\{\text{UnitPropagate}, \text{Unfounded}\}$ are sta-enforcing.

We are now ready to state the main result of this section.

**Theorem 3**
For any program $\Pi$, any type $w$, and any $w$-enforcing set of p-conditions $\mathcal{P}$, the graph $\text{DPT}_{\mathcal{P}, \Pi}$ checks the $w$-models of $\Pi$.

Theorems 2 and 3 give rise to families of valid solvers for deciding where classical, supported, or stable models exist for a program. For instance, for a non-disjunctive program $\Pi$, the graph $\text{DPT}_{\text{sm}, \Pi}$ coincides with the graph $\text{Sm}_{\Pi}$ (Lierler 2011) that captures computation of answer set solver smodels (Simons et al. 2002). The graph $\text{DPT}_{\text{sd}, \Pi}$ coincides with the graph $\text{atleast}_{\Pi}$ (Lierler 2011) that provides a procedure for deciding whether a non-disjunctive program has supported models. For a disjunctive program $\Pi$ the same single layer graph $\text{DPT}_{\text{sm}, \Pi}$ forms a procedure for deciding whether $\Pi$ has a stable model. Note, however, that generally the problem of deciding whether $l \in \text{Unfounded}(\Pi, L)$ is NP-complete for the case when $\Pi$ is disjunctive.

### 4.2 A Two-Layer Graph Template

We extend here the approach of Section 4.1 to capture two-layer methodology of disjunctive solvers.

**Definition 2**

Given a program $\Pi$, sets $\mathcal{P}_L$ and $\mathcal{P}_R$ of p-conditions, a generating function $g$, and a witness function $t$, a two-layer template graph $\text{STT}_{\mathcal{P}_L : g, \mathcal{P}_R : t}(\Pi)$ is a graph defined as follows:
\[ Propagate_L \ (L, \emptyset)_L \Rightarrow (Ll, \emptyset)_L \quad \text{if } l \in P_L(g(\Pi), L) \]
\[ Propagate_R \ (L, R)_R \Rightarrow (L, Rl)_R \quad \text{if } l \in P_R(t(\Pi, L), R) \]

Fig. 6. Transition rules of the graph template \( \text{STT}^{P_L \cdot g \cdot P_R \cdot t}_{\Pi} (\Pi) \).

- The set of nodes is, as in the previous two-layer graphs, the set of states relative to \( \text{atoms}(g(\Pi)) \) and \( \text{atoms}(t, \Pi, \text{atoms}(g(\Pi))) \); and
- The transition rules are the rules presented in Figure 4 except the rules \( \text{Unit}_L \) and \( \text{Unit}_R \), that are replaced by the rules \( \text{Propagate}_L \) and \( \text{Propagate}_R \) presented in Figure 6.

Description of the Template. We call the state \((\emptyset, \emptyset)_L\) initial. Note how the rules \( \text{Propagate}_L \) and \( \text{Propagate}_R \) in \( \text{STT}^{P_L \cdot g \cdot P_R \cdot t}_{\Pi} (\Pi) \) refer to the parameters \( P_L, P_R, g \) and \( t \) of the graph template. Varying these parameters will allow us to specify transition systems that capture different disjunctive answer set solvers. Intuitively, the parameters \( P_L \) and \( P_R \) are sets of p-conditions defining a propagation rule on generate and test side of computation, respectively.

The instantiation \( \text{STT}^{up \cdot g^C \cdot t^C}_{up, t^C} (\Pi) \) of the two-layer graph template results in \( \text{DP}_2^\Pi \). Indeed, the graphs share the same nodes. Also their rules \( \text{Conclude}_L \), \( \text{Conclude}_R \), \( \text{Decide}_L \), \( \text{Decide}_R \), \( \text{Backtrack}_L \), \( \text{Backtrack}_R \) and \( \text{Conclude}_R \) coincide. It is easy to see that a literal \( l \) is in \( up(g^C(\Pi), L) \) if and only if the transition rule \( \text{Unit}_L \) in \( \text{DP}_2^\Pi \) is applicable in \((L, \emptyset)_L\) and supports the transition to a state \((Ll, \emptyset)_L\). Thus, the transition rule \( \text{Propagate}_L \) supports the transition from \((L, \emptyset)_L\) to \((Ll, \emptyset)_L\) if and only if the transition rule \( \text{Unit}_L \) supports the same transition. A similar statement holds for the case of \( \text{Propagate}_R \) and \( \text{Unit}_R \).

Recall that in Section 3.2 we showed that cmodels implementing backtracking can be defined using the graph \( \text{DP}_2^\Pi \). The fact that instantiation \( \text{STT}^{up \cdot g^C \cdot t^C}_{up, t^C} (\Pi) \) coincides with \( \text{DP}_2^\Pi \) illustrates that the introduced template is sufficient for capturing existing solvers. Next section demonstrates that the proposed template is suitable for capturing gnt and dlv.

Instantiation: Approximating and Ensuring Pairs. In the definition of the two-layer template graph \( \text{STT}^{P_L \cdot g \cdot P_R \cdot t}_{\Pi} (\Pi) \) we pose no restrictions on its four key parameters: sets \( P_L, P_R \) of p-conditions, and generating and witness functions \( g, t \). In practice, when this template is utilized to model, characterize, and elicit disjunctive solvers these four parameters exhibit specific properties. We now introduce terminology that allows us to specify essential properties of these parameters that will translate into correctness of solvers captured by properly instantiated template. On the one hand, we introduce the conditions on generating and witness functions under which we call these functions “approximating” and “ensuring”, respectively. On the other hand, we couple these conditions with restrictions on sets of p-conditions so that we can speak of (i) approximating-pair \((P_g, g)\) for a set \( P_g \) of p-conditions and a generating function \( g \), and (ii) ensuring-pair \((P_t, t)\) for a set \( P_t \) of p-conditions and
a witness function \( t \). For such pairs, the template instantiation \( STT_{P_t}^{P_g}(\Pi) \) results in a graph that checks stable models of \( \Pi \). As a result, when we characterize such solvers as GNT and DLV by means of the two-layer template we focus on (i) specifying their generating and witness function as well as their sets of p-conditions, and (ii) illustrating that they form proper approximating and ensuring pairs. This also brings us to the realization that an inception of a novel solver can be triggered by a creation of a novel approximation and ensuring pairs or their combinations. We now make these ideas precise.

For types \( w \) and \( w_1 \), we say that a generating function \( g \) is \( w_1 \)-approximating with respect to type \( w \) if for any program \( \Pi \):

1. For any stable model \( L \) of \( \Pi \) there is a \( w_1 \)-model \( L_1 \) of \( g(\Pi) \) such that \( L = L_1|_{\text{atoms}(\Pi)} \); and
2. For any \( w_1 \)-model \( M \) of \( g(\Pi) \), \( M|_{\text{atoms}(\Pi)} \) is a \( w \)-model of \( \Pi \).

Consider the generating function \( cnfcomp(\Pi) \) that returns a CNF formula, which stands for the completion \( \text{comp}(\Pi) \) converted to CNF using straightforward equivalent transformations. In other words, \( cnfcomp(\Pi) \) consists of clauses of two kinds:

1. the rules \( A \leftarrow B \) of the program written as clauses \( A \lor B \), and
2. formulas of \( cnfcomp(\Pi) \) from (2) converted to CNF using the distributivity of disjunction over conjunction.\(^3\)

The function \( cnfcomp \) is \( cla \)-approximating with respect to \( sup \). Indeed,

1. any stable model of a program \( \Pi \) is also a \( cla \)-model of \( cnfcomp(\Pi) \), and
2. any \( cla \)-model of \( cnfcomp(\Pi) \) is a \( sup \)-model of \( \Pi \).

Since any supported model is also a classical model, the \( cnfcomp \) function is also \( cla \)-approximating with respect to \( cla \). Note that when a generating function \( g \) is \( w_1 \)-approximating with respect to \( w \), then enumerating all \( w_1 \)-models of \( g(\Pi) \) results in enumerating some \( w \)-models of \( \Pi \) modulo a restriction to \( \text{atoms}(\Pi) \).

For types \( w \) and \( w_1 \), and a witness function \( t \), we say that \( t \) is \( w_1 \)-ensuring with respect to \( w \) when for any set \( M \) of literals covering \( \Pi \) such that \( M|_{\text{atoms}(\Pi)} \) is a \( w \)-model of \( \Pi \), \( M|_{\text{atoms}(\Pi)} \) is a stable model of \( \Pi \) if and only if \( t(\Pi, M) \) results in a program that has no \( w_1 \)-model.

For instance, the witness function \( t_C \) is \( cla \)-ensuring with respect to \( cla \). Since any \( sup \)-model is also a \( cla \)-model, the function \( t_C \) is also \( cla \)-ensuring with respect to \( sup \). It is easy to see that when a witness function \( t \) is \( w_1 \)-ensuring with respect to \( w \), then given any \( w \)-model \( L \) of a program \( \Pi \) we may use the function \( t \) to test that \( L \) is also a stable model of \( \Pi \). Indeed, an application of \( t \) resulting in a program that has no \( w_1 \)-models translates into the statement that \( L \) is a stable model of \( \Pi \).

These newly defined concepts of approximating and ensuring functions provide the following characterization for the set of stable models of a program \( \Pi \).

\(^3\) It is essential that repetitions are not removed in the process of clausification. For instance, \( cnfcomp(a \leftarrow \text{not } a) = (a \lor \text{not } a) \land (\text{not } a \lor \text{not } a) \).
Proposition 4
For any types \( w, w_1 \) and \( w_2 \), generating function \( g \) that is \( w_1 \)-approximating with respect to \( w \), witness function \( t \) that is \( w_2 \)-ensuring with respect to \( w \), and program \( \Pi \), the set of all stable models of \( \Pi \) is
\[
\{ L \mid \text{\( L \) is a \( w_1 \)-model of \( g(\Pi) \) and \( t(\Pi, L) \) has no \( w_2 \)-models} \}.
\]

We now introduce the notion of ensuring and approximating pairs that permit an operational use of generating and witness functions, by matching them with a relevant set of propagators. We call a pair \((\mathcal{P}, g)\) of a set of p-conditions and a generating function an approximating-pair with respect to \( w_1 \) if for some type \( w_1 \), the set \( \mathcal{P} \) is \( w_1 \)-enforcing and the function \( g \) is \( w_1 \)-approximating with respect to \( w_1 \). For example, the pair \((\text{up}, \text{cnfcomp})\) is an approximating-pair with respect to \( \text{sup} \) as well as to \( \text{cla} \). The \((\text{up}, g^C)\) is also an approximating-pair with respect to \( \text{sup} \) as well as to \( \text{cla} \).

We call a pair \((\mathcal{P}, t)\) of a set of p-conditions and a witness function an ensuring-pair with respect to \( w_1 \) if for some type \( w_1 \), the set \( \mathcal{P} \) is \( w_1 \)-enforcing and the function \( t \) is \( w_1 \)-ensuring with respect to \( w_1 \). For example, the pair \((\text{up}, t^C)\) is an ensuring-pair with respect to any defined type.

We are now ready to state the main result of this section.

Theorem 4
For any program \( \Pi \), any type \( w \), any \((\mathcal{P}, g)\) approximating-pair with respect to \( w \), and any \((\mathcal{P}, t)\) ensuring-pair with respect to \( w \), the graph \( \text{STT}_{\mathcal{P}, g}^{P_g} (\Pi) \) checks the stable models of \( \Pi \).

Theorem 4 illustrates how the template \( \text{STT}_{\mathcal{P}, g}^{P_g} (\Pi) \) can serve as a framework for defining transitions systems that result in correct algorithms for deciding whether a program \( \Pi \) has a stable model. The facts that \((\text{up}, g^C)\) is an approximating-pair with respect to \( \text{cla} \) and that \((\text{up}, t^C)\) is an ensuring-pair with respect to \( \text{cla} \), together with Theorem 4, subsume the result of Proposition 3.

We now state propositions that capture interesting properties about states of the graph \( \text{STT}_{\mathcal{P}, g}^{P_g} (\Pi) \). The former proposition concerns states with the label \( \mathcal{L} \), the latter concerns states with the label \( \mathcal{R} \).

Proposition 5
For any type \( w \), generating function \( g \), witness function \( t \), \( w \)-enforcing set of p-conditions \( \mathcal{P}_g \), set of p-conditions \( \mathcal{P}_t \), and program \( \Pi \), if no left-rule is applicable in some state \((l_1, \cdots, l_{k_1}, r_1, \cdots, r_{k_2})\) in \( \text{STT}_{\mathcal{P}_g, t}^{P_g} (\Pi) \) reachable from the initial state, then \( l_1, \cdots, l_{k_1} \) is a \( w \)-model of \( g(\Pi) \).

Proposition 6
For any types \( w_1 \) and \( w_2 \), generating function \( g \) witness function \( t \), \( w_1 \)-enforcing set of p-conditions \( \mathcal{P}_g \), \( w_2 \)-enforcing set of p-conditions \( \mathcal{P}_t \), program \( \Pi \), and a state \((l_1, \cdots, l_{k_1}, r_1, \cdots, r_{k_2})\) in \( \text{STT}_{\mathcal{P}_g, t}^{P_g} (\Pi) \) reachable from the initial state, the following conditions hold:

(a) \( t(\Pi, l_1, \cdots, l_{k_1}) \) is defined,
(b) \( r_1, \ldots, r_{k_2} \) is a set of literals over \( t(\Pi, L) \),
(c) \( l_1, \ldots, l_{k_1} \) is a \( w_1 \)-model of \( g(\Pi) \), and
(d) If no right-rule is applicable to \((l_1, \ldots, l_{k_1}, r_1, \ldots, r_{k_2})_R\) then \( r_1, \ldots, r_{k_2} \) is a
\( w_2 \)-model of \( t(\Pi, l_1, \ldots, l_{k_1}) \).

5 Applications of the Template

Section 3.2 illustrates how cmodels implementing backtracking can be defined
using the graph \( DP^2_{\Pi} \), while the previous section states that the instantiation
\( STT_{sup, g^C}(\Pi) \) of the two-layer graph template results in \( DP^2_{\Pi} \). Thus, this
template is suitable for capturing computations of cmodels. In this section, we show
how the template also captures the solvers GNT and DLV without backjumping.
Then, we discuss how the framework facilitates the design of new abstract solvers
and their comparison, by means of inspecting the structures of the related graphs.

Abstract GNT. We now show how the procedure underlying disjunctive solver GNT
can be captured by the two-layer template. Unlike solver cmodels that uses the
dpll procedure for generating and testing, system GNT uses the smodels procedure
for respective tasks. Recall that the smodels procedure finds stable models for non-
disjunctive logic programs, while the dpll procedure finds classical models. The
graph \( SM^2_{\Pi} \) (Section 4.1) captures the computation underlying smodels just as the
graph \( DP^2_{\Pi} \) captures the computation underlying dpll. It forms a basis for devising
the transition system suitable to describe GNT. The graph describing the general
structure of GNT is obtained from the graph template \( STT_{sm, t}^{sm, g}(\Pi) \) that rely on the
set \( sm \) of p-conditions.

Janhunen et al. (2006) define the generating function \( g^G \) and the witness function
\( t^G \) used in GNT. We present these definitions in (6) and (7). For a disjunctive
program \( \Pi \), by \( \Pi_N \) we denote the set of non-disjunctive rules of \( \Pi \), by \( \Pi_D \) we
denote the set of disjunctive rules \( \Pi \setminus \Pi_N \). For each atom \( a \) in \( atoms(\Pi) \) let \( a^r \) and \( a^s \) be new atoms.

\[
g^G(\Pi) = \{ a \leftarrow B, \text{not } a^r \mid A \vee a \leftarrow B \in \Pi_D \} \cup \\
\{ a^r \leftarrow \text{not } a \mid A \vee a \leftarrow B \in \Pi_D \} \cup \\
\{ \leftarrow A, B \mid a \leftarrow B \in \Pi_D \} \cup \\
\Pi_N \cup \\
\{ a^s \leftarrow A \setminus \{ a \}, B \mid A \vee a \leftarrow B \in \Pi_D \} \cup \\
\{ \leftarrow a, \text{not } a^r \mid a \vee A \leftarrow B \in \Pi_D \} \}
\]

4 The graph template \( STT_{sm, g}(\Pi) \) corresponds to the graph \( SM^2_{g(\Pi), t} \) defined in (Brochenin
et al. 2014).
5 The presented functions \( g^G \) and \( t^G \) capture the essence of functions Gen and Test defined by
Janhunen et al., but they are not identical. Our language of disjunctive programs includes rules
with empty heads. This allows us a more concise description.
Corollary 1
For any $\Pi$ the graph $SM^2_{\Pi}$ checks the stable models of $\Pi$.

6 Corollary 1 corresponds to Theorem 5 in (Brochenin et al. 2014).
Abstract DLV without Backjumping. This section introduces graphs that capture the answer set solver DLV without backjumping. The generate layer, i.e., the left-rule layer, is reminiscent to the smodels algorithm except it does not use Unfounded. The test layer applies the dpll procedure to a witness formula.

The graph templates $STT_{sd,g}^{up,t,D}(Π)$ describes the general structure of DLV. The generating function $g^D$ is the identity function as in (8), and the witness function $t^D$ follows in (9).

$$g^D(Π) = Π$$ (8)

$$t^D(Π, M) = \{ (B \cap M^+) \cup \bar{A} \mid A \leftarrow B \in Π^{M^+}, B \subseteq M, A' = A \cap M^+ \} \cup \{ (M_{\text{atoms}(Π)}) \bar{A} \}$$ (9)

Following the results from Faber (2002) and Koch et al. (2003), the generating function $g^D$ is sup-approximating with respect to $cla$ while the witness function $t^D$ is cla-ensuring with respect to $cla$. The pair $(sd, g^D)$ is an approximating-pair with respect to $cla$, while $(up, t^D)$ is an ensuring-pair with respect to $cla$. The result below immediately follows from Theorem 4.7

Corollary 2

For any $Π$ the graph $STT_{sd,g}^{up,t,D}(Π)$ checks the stable models of $Π$.

7 Corollary 2 corresponds to Theorem 6 in (Brochenin et al. 2014).
This corollary is an alternative proof of correctness for the Dlv algorithm previously stated by Faber (2002) and Koch et al. (2003) in terms of pseudo-code. Figure 8 presents an example of a path through one of the graph describing abstract Dlv.

Designing new Graphs and Comparing Graphs. The two-layer graph template can be conveniently used to define new abstract solvers. For instance, one may choose to combine \((up, g^c)\) with \((sn, t^c)\) to obtain a solver captured by the graph template \(STT^{up,g^c}_{sn,t^c}(II)\). Theorem 4 provides a proof of correctness for the procedure summarized by this family of graphs. More generally, to obtain a new solver one can combine any approximating-pair on the left side of the graphs with any ensuring-pair on the right side with respect to the same type. For instance, for any pair \((P, t)\) that is ensuring with respect to \(cla\), the family of graphs \(STT^{up, cnfcomp}_{P, t}(II)\) captures a correct procedure for a disjunctive answer set solver.

In the following, we illustrate how abstract solvers can serve also as a convenient tool for comparing search procedures from an abstract point of view, by means of comparison to the related graphs. In this respect we now state the result that illustrates a strong relation between CMODELS and Dlv. Indeed, their generate layer:

**Theorem 5**
For any \((P, t)\) ensuring-pair with respect to \(cla\), and any program \(\Pi\), the graphs \(STT^{up, cnfcomp}_{P, t}(\Pi)\) and \(STT^{sd, g^p}_{P, t}(\Pi)\) are identical graphs.

6 Proofs

6.1 Proof of Theorem 2

We start by stating several lemmas that will be instrumental in constructing arguments for Theorem 2. Recall that \(up = \{UnitPropagate\}\).

**Lemma 1**
The set \(up\) is \(cla\)-complete.

In other words, for any program \(\Pi\) and any complete and consistent set \(M\) of literals over \(atoms(\Pi)\), the set \(M\) is a \(cla\)-model of \(\Pi\) iff \(UnitPropagate(\Pi, M) = \emptyset\).

**Proof**
Left-to-right: Let \(M\) be a \(cla\)-model of \(\Pi\). Our proof is by contradiction. Assume that \(UnitPropagate(\Pi, M) \neq \emptyset\). Take any literal \(l\) from this set. Then, the literal \(l\) is such that it does not belong to \(M\). Also, there is a rule in \(\Pi\) that is equivalent to a clause \(C \lor l\) so that all the literals of \(C\) occur in \(M\). Since \(M\) is a \(cla\)-model of \(\Pi\), we conclude that \(l \in M\). We derive a contradiction.

Right-to-left: Let \(UnitPropagate(\Pi, M) = \emptyset\). By contradiction. Assume that \(M\) is not a \(cla\)-model of \(\Pi\). Then there is a rule in \(\Pi\) that is equivalent to a clause \(C \lor l\) so that all the literals of \(C\) as well as \(l\) occur in \(M\) (indeed, \(M\) is a complete set of literals over \(atoms(\Pi)\) that does not satisfy some rule in \(\Pi\)). Since \(M\) is consistent, \(l \notin M\). It follows that \(l \in UnitPropagate(\Pi, M)\). We derive a contradiction. □
Lemma 2
For any program $\Pi$, any atom $a$, and any sets $M$ and $M'$ of literals such that $M \subseteq M'$, if a rule in $\Pi$ is not a supporting rule for $a$ with respect to $M$ then this rule is also not a supporting rule for $a$ with respect to $M'$.

Proof
By contradiction. Assume that there is a rule $A \lor a \leftarrow B$ in $\Pi$ such that it is not a supporting rule for $a$ with respect to $M$ but it is a supporting rule for $a$ with respect to $M'$. It follows that $M \cap (\overline{B} \cup A) \neq \emptyset$, while $M' \cap (\overline{B} \cup A) = \emptyset$. This contradicts the fact that $M \subseteq M'$.

We now generalize Lemma 4 from Lierler (2008) to the case of disjunctive programs.

Lemma 3
For any unfounded set $U$ on a consistent set $L$ of literals w.r.t. a program $\Pi$ and any consistent and complete set $M$ of literals over atoms($\Pi$), if $L \subseteq M$ and $M \cap U \neq \emptyset$, then $M$ is not a stable model of $\Pi$.

Proof
By contradiction. Assume that $M$ is a stable model of $\Pi$. Then, $M$ is a classic model of $\Pi$ also. By Theorem 1, $M$ is such that there is no non-empty subset of $M^+$ such that it is an unfounded set on $M$ w.r.t. $\Pi$. Since $M \cap U \neq \emptyset$, it follows that $M \cap U$ is not an unfounded set on $M$ w.r.t. $\Pi$. It follows that for some rule $a \lor A \leftarrow B \in \Pi$ such that $a \in M \cap U$ all of the following conditions hold

1. $M \cap \overline{B} = \emptyset$,
2. $M \cap U \cap B = \emptyset$, and
3. $(A \setminus (M \cap U)) \cap M = \emptyset$.

Since $M \cap \overline{B} = \emptyset$ and $L \subseteq M$ it follows that $L \cap \overline{B} = \emptyset$. Since $M \cap \overline{B} = \emptyset$ and the fact that $M$ is consistent and complete set of literals over atoms($\Pi$), $B^+ \subseteq M$. Consequently $U \cap B^+ = M \cap U \cap B^+ = \emptyset$. Since $L \subseteq M$ and $(A \setminus (M \cap U)) \cap M = \emptyset$, it follows that $(A \setminus U) \cap L = \emptyset$. Consequently, the set $U$ is not an unfounded set on $L$.

We are now ready to introduce the proof of Theorem 2.

Proof of Theorem 2
Statement 1. We have to show that the set $up$ is cla-enforcing. Lemma 1 states that the set up is cla-complete. Thus, we only ought to illustrate that up is cla-sound. Let $\Pi$ be any program, $M$ be any set of literals, $M'$ be any cla-model of $\Pi$ such that $M \subseteq M'$. We have to show that $up(\Pi, M) \subseteq M'$. Let $l$ be any literal in $up(\Pi, M)$. We now show that $l \in M'$. The $p$-condition $UnitPropagate$ is the only member of the set $up$. Thus, $up(\Pi, M) = UnitPropagate(\Pi, M)$. It follows that $l \in UnitPropagate(\Pi, M)$. By the conditions of $UnitPropagate$ definition, there is a rule in $\Pi$ that is equivalent to a clause $C \lor l$ so that all the literals of $C$ occur in
M. Since $M \subseteq M'$, it follows that all the literals of $\overline{C}$ occur in $M'$. From the fact that $M'$ is $\text{cla}$-model of $\Pi$ it follows that $M' \models C \cup l$. Consequently, $l \in M'$.

Statement 2. We have to show that the subsets of $\text{sd}$ containing \{UnitPropagate, AllRulesCancelled\} are $\text{sup}$-enforcing. We first illustrate this property for the set \{UnitPropagate, AllRulesCancelled\}. We call this set $\text{ua}$. We start by showing that the set $\text{ua}$ is $\text{sup}$-sound. Let $\Pi$ be any program, $M$ be any set of literals, $M'$ be any $\text{sup}$-model of $\Pi$ such that $M \subseteq M'$. We have to illustrate that the set $\text{ua}(\Pi, M)$ is a subset of $M'$. Consider any literal $l$ in the set $\text{ua}(\Pi, M)$. We now show that $l$ is also in $M'$.

Case 1. $l \in \text{UnitPropagate}(\Pi, M)$. Since $M'$ is a $\text{sup}$-model, $M'$ is also a $\text{cla}$-model. The rest of the argument follows the lines of proof in Statement 1, which illustrates that up is $\text{cla}$-sound.

Case 2. $l \in \text{AllRulesCancelled}(\Pi, M)$. $l$ has the form $\neg a$. By the conditions of AllRulesCancelled definition, it follows that there is no rule in $\Pi$ supporting $a$ with respect to $M$. By Lemma 2, we derive that there is no rule in $\Pi$ supporting $a$ with respect to $M'$. From the fact that $M'$ is $\text{sup}$-model of $\Pi$ it follows that $\neg a \in M'$. (Indeed, $a$ may not be a member of $M'$, while $M'$ is a complete set of literals over $\text{atoms}(\Pi)$.)

Second, we show that the set $\text{ua}$ is $\text{sup}$-complete. Let $\Pi$ be any program, $M$ be any complete and consistent set of literals over $\text{atoms}(\Pi)$. We now show that $M$ is $\text{sup}$-model of $\Pi$ iff $\text{ua}(\Pi, M) = \emptyset$.

Left-to-right: Let $M$ be a $\text{sup}$-model of $\Pi$. By contradiction. Assume that the set $\text{ua}(\Pi, M)$ is not empty. Then there is a literal $l$ in this set.

Case 1. $l \in \text{UnitPropagate}(\Pi, M)$. Since $M$ is also $\text{cla}$-model of $\Pi$, by Lemma 1 we derive a contradiction.

Case 2. $l \in \text{AllRulesCancelled}(\Pi, M)$. $l$ has the form $\neg a$. By the conditions of AllRulesCancelled definition, it follows that (i) literal $\neg a$ is such that it does not belong to $M$, and (ii) there is no supporting rule in $\Pi$ for $a$ with respect to $M$. Since $M$ is a $\text{sup}$-model of $\Pi$, we conclude from (ii) that $\neg a \in M$. This contradicts (i).

Right-to-left: Assume $\text{ua}(\Pi, M) = \emptyset$. By contradiction. Assume that $M$ is not a $\text{sup}$-model of $\Pi$. Then either $M$ is not a $\text{cla}$-model of $\Pi$ or there is an atom $a \in M^+$ such that there is no supporting rule in $\Pi$ for $a$ with respect to $M$. In the former case, when $M$ is not a $\text{cla}$-model of $\Pi$, by Lemma 1 we derive a contradiction. In the latter case, it follows that $\neg a \in \text{AllRulesCancelled}(\Pi, M)$ by the conditions of the AllRulesCancelled definition. We derive a contradiction.

We now show that the set $\text{sd}$ is $\text{sup}$-enforcing. We start by claiming that the set $\text{sd}$ is $\text{sup}$-sound. Let $\Pi$ be any program, $M$ be any set of literals, $M'$ be any $\text{sup}$-model of $\Pi$ such that $M \subseteq M'$. We have to illustrate that the set $\text{sd}(\Pi, M)$ is a subset of $M'$. Consider any literal $l$ in the set $\text{sd}(\Pi, M)$. We show that $l$ is also in $M'$. Given a proof that $\text{ua}$ is $\text{sup}$-sound, it is only left to be proved that for any literal $l$ that is in $\text{BackchainTrue}(\Pi, M)$, it also holds that $l \in M'$. Consider literal $l \in \text{BackchainTrue}(\Pi, M)$. By the definition of $\text{BackchainTrue}$ it follows that there is a rule $r = A \cup a \leftarrow B$ in $\Pi$ so that (i) $a \in M$, and (ii) either $\overline{l} \in A$ or $l \in B$ and, (iii) no other rule in $\Pi$ is supporting $a$ with respect to $M$. By Lemma 2
and (iii), we derive that every rule other than \(r\) is such that it is not a supporting rule for \(a\) with respect to \(M'\). By (i) and the fact that \(M \subseteq M'\), \(a \in M'\). Since \(M'\) is a sup-model of \(\Pi\), it follows that \(M \cap (B \cup \mathcal{X}) = \emptyset\). By the fact that \(M'\) is a consistent and complete set of literals over \(\text{atoms}(\Pi)\) we conclude that \(B \cup \mathcal{X} \subseteq M\).

By (ii), \(l \in M'\).

**Statement 3.** We have to show that the subsets of \(sm\) containing \(\{\text{UnitPropagate}, \text{Unfounded}\}\) are sta-enforcing. We only illustrate this for the set \(\{\text{UnitPropagate}, \text{Unfounded}\}\). We call this set \(uu\). The proof for other sets (i) relies on the fact that any sta-model is also a cla and sup-model and (ii) follows the ideas presented in the proof of Statement 2.

We start by showing that the set \(uu\) is sta-sound. Let \(\Pi\) be any program, \(M\) be any set of literals, \(M'\) be any sta-model of \(\Pi\) such that \(M \subseteq M'\). We have to illustrate that the set \(uu(\Pi, M)\) is a subset of \(M'\). Consider any literal \(l\) in the set \(uu(\Pi, M)\). We now show that \(l\) is also in \(M'\).

**Case 1.** \(l \in \text{UnitPropagate}(\Pi, M)\). Since \(M'\) is a sta-model, \(M'\) is also a cla-model. The rest of the argument follows the lines of proof in Statement 1, which illustrates that up is cla-sound.

**Case 2.** \(l \in \text{Unfounded}(\Pi, M)\). Literal \(l\) has the form \(\neg a\). By the conditions of \(\text{Unfounded}\) definition, it follows that there is a set \(X\) containing \(a\) such that \(X\) is unfounded with respect to \(\Pi\). By Lemma 3 and the fact that \(M'\) is sta-model of \(\Pi\) it follows that \(\neg a \in M'\). (Indeed, consider a simple argument by contradiction.)

Second, we show that the set \(uu\) is sta-complete. Let \(\Pi\) be any program, \(M\) be any complete and consistent set of literals over \(\text{atoms}(\Pi)\). We now show that \(M\) is sta-model of \(\Pi\) iff \(uu(\Pi, M) = \emptyset\).

**Left-to-right:** Let \(M\) be a sta-model of \(\Pi\). By contradiction. Assume that the set \(uu(\Pi, M)\) is not empty. Then there is a literal \(l\) in this set.

**Case 1.** \(l \in \text{UnitPropagate}(\Pi, M)\). Since \(M\) is also cla-model of \(\Pi\), by Lemma 1 we derive a contradiction.

**Case 2.** \(l \in \text{Unfounded}(\Pi, M)\). Literal \(l\) has the form \(\neg a\). By the conditions of \(\text{Unfounded}\) definition, it follows that (i) literal \(\neg a\) is such that it does not belong to \(M\), and (ii) there is a set \(X\) containing \(a\) such that \(X\) is unfounded with respect to \(\Pi\). Since \(M\) is a sta-model of \(\Pi\), we conclude from (ii) that \(\neg a \in M\). This contradicts (i).

**Right-to-left:** Assume that \(uu(\Pi, M) = \emptyset\). By contradiction. Assume that \(M\) is not a sta-model of \(\Pi\). By Theorem 1, either \(M\) is not a cla-model of \(\Pi\) or there is a non-empty subset of \(L^+\) that is an unfounded set on \(L\) with respect to \(\Pi\). In the former case, when \(M\) is not a cla-model of \(\Pi\), by Lemma 1 we derive a contradiction. In the latter case, it follows that there is some atom \(a\) in an existing unfounded set so that \(\neg a \in \text{Unfounded}(\Pi, M)\) by the conditions of the \(\text{Unfounded}\) definition. We derive a contradiction. \(\square\)
6.2 Proofs of Theorems 3, 4, Propositions 2, 4, 5, 6

We start by the proof of Theorem 4. We skip the proof of Theorem 3 as it relies on the same proof techniques that proof of Theorem 4 exhibits. The proof of Theorem 4 relies on auxiliary lemmas as well as proofs of Propositions 4, 5, 6 that follow. We conclude this section with the proof of Proposition 2.

Lemma 4
Let \( g \) be a generating function and \( t \) be a witness function.

Let \( \mathcal{P}_g \) and \( \mathcal{P}_t \) be sets of p-conditions.

Then for any \( \Pi \), the graph \( STT_{\mathcal{P}_t,g}(\Pi) \) is finite and acyclic.

Proof
Consider the states of the graph \( STT_{\mathcal{P}_t,g}(\Pi) \). The string \( L \) of states of the form \((L,R)s\) or of the type \( Ok(L) \) is built over a set of atoms which is bounded by the size of \( \Pi \). Also, \( L \) does not allow repetitions. Thus, there is a finite number of possible strings \( L \) in the states \((L,R)s\) or \( Ok(L) \). It immediately follows that there is a finite number of states \( Ok(L) \) in \( STT_{\mathcal{P}_t,g}(\Pi) \).

Consider the right side of a state of the form \((L,R)s\). Since \( t(\Pi,L) \) has a finite number of atoms and there is a finite number of possible \( L \), the set of atoms over which \( R \) is built is finite. Consequently, there is a finite number of possible \( R \). We conclude that there is a finite number of possible states \((L,R)s\). Thus the set of states is finite in \( STT_{\mathcal{P}_t,g}(\Pi) \).

For any string \( L \) of literals, by \(|L|\) we denote the length of this string. Any string \( L \) of literals can be written \( L_0|L_1|\ldots|L_k \), where \((L_i)_{1 \leq i \leq k} \) contains all the decision literals of \( L \). Let us call \( v(L) \) the sequence \(|L_0|,|L_1|\ldots|L_k|\). We then write \( L \preceq L' \) iff \( v(L) \preceq_{lex} v(L') \) where \( \preceq_{lex} \) is the lexicographic order. Since the length of the sequence \( v(L) \) is bounded by the finite number of possible decision literals, this is a well-founded order. Finally, we say that \((L,R)s \preceq (L',R',s') \) iff \((L,R,s) \preceq_{lex} (L',R',s') \) where \( \preceq_{lex} \) is the lexicographic order and \( L \preceq R \). This is clearly well-founded as it is the lexicographic composition of well-founded orders.

If there is a transition from \((L,R)s\) to \((L',R')s'\) then \((L,R)s \preceq (L',R',s') \) and \((L,R)s \neq (L',R')s'\). This can be checked simply for each of the rules. Since the order is well-founded, there is no infinite path in the graph. Consequently, the graph is acyclic. \( \Box \)

Proof of Proposition 5
We first show that \( l_1,\ldots,l_{k_1} \) is consistent. By contradiction. Assume that \( l_1,\ldots,l_{k_1} \) is inconsistent. Then since \( Conclude_L \) is not applicable \( l_1,\ldots,l_{k_1} \) contains at least one decision literal. We now define \( i \) as \( l_1,\ldots,l_{k_1} = l_1,\ldots,l_{i-1},l_i^\Delta,l_{i+1},\ldots,l_{k_1} \) where \( l_i^\Delta \) is the rightmost decision literal. Since \( Backtrack_L \) is not applicable \( l_1,\ldots,l_{k_1} \) contains no decision literal. We derive a contradiction.

Since \( Decide_L \) is not applicable and \( l_1,\ldots,l_{k_1} \) is consistent, \( l_1,\ldots,l_{k_1} \) assigns all the atoms of \( atoms(g(\Pi)) \). As a consequence \( l_1,\ldots,l_{k_1} \) is a consistent and complete set of literals that covers \( atoms(g(\Pi)) \). Finally, \( Propagate_L \) is not applicable. So
Lemma 5

$P_g(I,l_1\cdots l_{k_1})$ is the empty set. Since $P_g$ is $w$-enforcing and hence $w$-complete, $l_1\cdots l_{k_1}$ is a $w$-model of $g(I)$.

Proof of Proposition 6

Statements (a – c) We prove these statements by induction on the length of a path in the graph $STTP_{P,t}^g(I)$. Since the statements trivially hold in the initial state of the graph, we only have to prove that all transition rules of $STTP_{P,t}^g(I)$ preserve the properties.

Statement (c) trivially holds for all transitions but Crossing-rules $RL$. Statements (a) and (b) trivially hold for transitions due to Left rules, Crossing-rules $RL$, $Conclude_R$, $Conclude_{RL}$.

Consider an edge due to one of the Right rules or Crossing-rules $LR$ from state $S = (l_1^0 \cdots r_{k_1}, l_2^0 \cdots r_{k_2})$ to state $S' = (l_1, \cdots l_{k_1}, r_1, \cdots r_{k_2})_R$ so that the statements (a) and (b) hold on $S$ (an inductive hypothesis). For the Right rules (excluding $Conclude_R$), the left side of the state remains unchanged. Thus, by induction hypothesis (a) immediately follows. Similarly, it is easy to see from the conditions of these rules that they also preserve property (b). We now illustrate that the $Cross_{LR}$ preserves (a – c).

Case $Cross_{LR}$: It follows that (i) $s_0 = \mathcal{L}$, (ii) $l_1, \cdots l_{k_1} = l_1^0 \cdots l_{k_1}$, (iii) no left rule applies to $S$, (iv) $r_1, \cdots r_{k_2} = r_1^0 \cdots r_{k_2}$, (v) $\emptyset$. By Proposition 5, (i, ii), and (iii) we conclude that $l_1^0 \cdots l_{k_1}$ is a $w_1$-model of $g(I)$. By (ii), it follows that $l_1 \cdots l_{k_1}$ is also a $w_1$-model of $g(I)$. Thus, (c) holds. From the definition of $g(I)$ it follows that the set $\{l_1, \cdots l_{k_1}\}$ of literals covers $I$. It follows that $t(I, l_1, \cdots l_{k_1})$ is defined. Thus (a) holds. From (iv), (b) trivially follows as the right side of the state is empty.

Statement (d) We first show that $r_1, \cdots r_{k_2}$ is consistent. By contradiction. Assume that $r_1, \cdots r_{k_2}$ is inconsistent. Then since $Conclude_R$ is not applicable, $r_1, \cdots r_{k_2}$ contains at least one decision literal. We now define $i$ as $r_1, \cdots r_{k_2} = r_1, \cdots r_{i-1}, r^\Delta_i, r_{i+1}, \cdots r_{k_2}$ where $r^\Delta_i$ is the rightmost decision literal. Since the rule $Backtrack_R$ is not applicable $r_1, \cdots r_{k_2}$ contains no decision literal. We derive a contradiction.

Since $Decide_R$ is not applicable and $r_1, \cdots r_{k_2}$ is consistent, by (b) $r_1, \cdots r_{k_2}$ assigns all the atoms of $atoms(t(I, l_1, \cdots l_{k_1}))$. Thus, $r_1, \cdots r_{k_2}$ is a consistent and complete set of literals over $atoms(t(I, l_1, \cdots l_{k_1}))$. Finally, $Propagate_R$ is not applicable. So $P_t(t(I, l_1, \cdots l_{k_1}), r_1, \cdots r_{k_2})$ is the empty set. Since $P_t$ is $w_2$-enforcing and hence $w_2$-complete, $r_1, \cdots r_{k_2}$ is a $w_2$-model of $t(I, l_1, \cdots l_{k_1})$.

Lemma 5

Let $w_1$ and $w_2$ be some types in \{ela, sup, sta\}.

Let $g$ be a generating function and $t$ be a witness function.

Let $P_g$ be a $w_1$-enforcing set of $p$-conditions and $P_t$ be a $w_2$-enforcing set of $p$-conditions.

Let $I$ be a program.
Let \( (l_1, \ldots, l_{k_1}, r_1, \ldots, r_{k_2}) \) be a state of \( \text{STT}^\mathcal{P}_\mathcal{E}_\mathcal{S}(I) \) reachable from the initial state.

Then:

(a) any \( w_2 \)-model of \( t(I, l_1, \ldots, l_{k_1}) \) satisfies \( r_i \) if it satisfies all decision literals \( (r_j)^\Delta \) with \( j \leq i \).

(b) Any \( w_1 \)-model \( L \) of \( g(I) \) such that \( t(I, L) \) has no \( w_2 \)-model satisfies \( l_i \) if it satisfies all decision literals \( t_j^\Delta \) with \( j \leq i \).

**Proof**

We prove statements (a) and (b) by induction on the length of a path in the graph \( \text{STT}^\mathcal{P}_\mathcal{E}_\mathcal{S}(I) \) from the initial state. Since the statements trivially hold in the initial state of the graph, we only have to prove that all transition rules of \( \text{STT}^\mathcal{P}_\mathcal{E}_\mathcal{S}(I) \) preserve the properties.

Consider an edge from the state \( S = (l_1^0, \ldots, l_{k_1}^0, r_1^0, \ldots, r_{k_2}^0) \) to the state \( S' = (l_1, \ldots, l_{k_1}, r_1, \ldots, r_{k_2}) \) so that the statements (a) and (b) hold on \( S \) (an inductive hypothesis).

The statement (a) trivially holds for the case of transitions due to \( \text{Conclude}_\mathcal{L} \), \( \text{Conclude}_\mathcal{R} \), \( \text{Conclude}\mathcal{E} \).

For the case of transition rules \( \text{Cross}_{\mathcal{LR}} \), \( \text{Backtrack}_{\mathcal{R}} \), \( \text{Decide}_{\mathcal{R}} \), \( \text{Propagate}_{\mathcal{R}} \) it holds that \( l_1, \ldots, l_{k_1} = l_1^0, \ldots, l_{k_1}^0 \). So by the induction hypothesis, (b) trivially holds on \( (l_1, \ldots, l_{k_1}, r_1, \ldots, r_{k_2}) \). For these rules, we are left to show that (a) holds on \( (l_1, \ldots, l_{k_1}, r_1, \ldots, r_{k_2}) \). Note that for the case of \( \text{Backtrack}_{\mathcal{R}} \), \( \text{Decide}_{\mathcal{R}} \), \( \text{Propagate}_{\mathcal{R}} \), by Proposition 6 (a) it follows that \( t(I, l_1, \ldots, l_{k_1}) \) is defined.

**Case Cross_{\mathcal{LR}}:** It follows that \( r_1, \ldots, r_{k_1} = r_1^0, \ldots, r_{k_1}^0 = \emptyset \). Consequently, (a) holds as right side of the state is empty.

**Case Backtrack_{\mathcal{R}}:** In this case, there is an index \( i \) such that \( r_1^0, \ldots, r_{k_2}^0 = r_1^1, \ldots, r_{i-1}^0, (r_i)^\Delta, r_{i+1}^0, \ldots, r_{k_2}^0 \) and \( r_1, \ldots, r_{k_2-1} = r_1^1, \ldots, r_{i-1} \). Also, by the conditions of \( \text{Backtrack}_{\mathcal{R}} \), the string of literals \( r_1^1, \ldots, r_{k_2}^0 \) is inconsistent. Let \( M \) be a \( w_2 \)-model of \( t(I, l_1, \ldots, l_{k_1}) \). Let \( r_j \) be a literal of \( r_1, \ldots, r_{k_1} \). Assume \( M \) satisfies all decision literals \( (r_j)^\Delta \) with \( j' \leq j \). By the induction hypothesis, if \( j \neq k_2 \) then \( M \) satisfies \( r_j \). It remains to prove that this is also true when \( j = k_2 \). Assume \( M \) satisfies all the decision literals of \( r_1, \ldots, r_{k_2-1} \). Then \( M \) satisfies all the literals of \( r_1, \ldots, r_{k_2-1} \). They include all the decision literals of \( r_1, \ldots, r_{k_2-1} \). Therefore, \( M \) also satisfies \( r_{k_2} \).

None of the literals \( r_{k_2+1}^0, \ldots, r_{k_2}^0 \) is a decision literal. Additionally, \( r_1, \ldots, r_{k_2} = r_1^1, \ldots, r_{k_2-1}^0, \overline{r_k^0} \). Since \( M \) satisfies all the literals of \( r_1, \ldots, r_{k_2-1} \), it satisfies all the literals of \( r_1^1, \ldots, r_{k_2-1}^0 \). Since \( r_{k_2}^0, \ldots, r_{k_2}^0 \) is inconsistent, \( M \) cannot satisfy all of its literals, so \( M \) does not satisfy at least one literal of \( r_1^1, \ldots, r_{k_2}^0 \). By the contraposition of the induction hypothesis (a), and since none of the literals \( r_{k_2+1}^0, \ldots, r_{k_2}^0 \) is a decision literal, one of the literals not satisfied by \( M \) has to be \( r_k^0 \). So \( M \) must satisfy \( \overline{r_k^0} \), that is \( r_{k_2} \).

**Case Decide_{\mathcal{R}}:** Obvious.
Case Propagate$_R$. Let $M$ be a $w_2$-model of $t(\Pi, l_1, \ldots, l_k)$. Assume $M$ satisfies all the decision literals of $r_1, \ldots, r_{k_2}$. Since for any propagator condition $r_{k_2}$ is not a decision literal, they are the decision literals of $r_1, \ldots, r_{k_2-1}$. So $M$ satisfies all the literals of $r_1, \ldots, r_{k-1}$ by the induction hypothesis. In other words $\{r_1, \ldots, r_{k-1}\} \subseteq M$. Proving that $M$ satisfies $r_{k_2}$ will complete the proof. We are given that $P_t$ is $w_2$-enforcing and hence $w_2$-sound. By definition of $w_2$-soundness and the fact that $\{r_1, \ldots, r_{k-1}\} \subseteq M$, it follows that $P_t(\Pi, \{r_1, \ldots, r_{k-1}\}) \subseteq M$. Since $r_{k_2} \in P_t(\Pi, \{r_1, \ldots, r_{k-1}\})$, also $r_{k_2} \in M$. In other words, $M$ satisfies $r_{k_2}$.

We are left to illustrate that transition rules Backtrack$_{\mathcal{RL}}$, Propagate$_{\mathcal{L}}$ preserve properties $(a)$ and $(b)$. Since all of these rules are such that the right side of the resulting state is $\emptyset$, clearly $(a)$ is preserved. We will only illustrate that Backtrack$_{\mathcal{RL}}$ preserves $(b)$ as the remaining cases for $(b)$ are similar to the arguments constructed above for the respective right rules and property $(a)$.

Case Backtrack$_{\mathcal{RL}}$. There is an index $i$ such that $l_1, \ldots, l_{k_1-1} = l_1^0, \ldots, l_{i-1}^0$ and $l_i^0, \ldots, l_{k^0} = l_i^1, \ldots, l_{i-1}^1, l_i^{01}, l_{i+1}^0, \ldots, l_{k^0}^0$. Let $M$ be a $w_1$-model of $g(\Pi)$ such that $t(\Pi, M)$ has no $w_2$-model. Assume that $M$ satisfies all the decision literals of $l_1, \ldots, l_k$. Since $l_k$ is not a decision literal, they are the decision literals of $l_1, \ldots, l_{k_1-1}$. So $M$ satisfies all the literals of $l_1, \ldots, l_{k_1-1}$ by the induction hypothesis. Showing that $M$ satisfies $l_{k_1}$ will complete the proof.

Since the transition is justified by Backtrack$_{\mathcal{RL}}$, by Proposition 6 (c), $l_1^0, \ldots, l_{k^0}$ is a $w_1$-model of $g(\Pi)$. By Proposition 6 (d) and the fact that no right-rule applies, $r_1^0, \ldots, r_{k_1}$ is a $w_2$-model of $t(\Pi, l_1, \ldots, l_{k_1})$. So $t(\Pi, l_1, \ldots, l_{k_1})$ has a $w_2$-model, hence $M$ does not satisfy all the literals of $l_1^0, \ldots, l_{k_1}^0$. Consequently, since $M$ satisfies all the literals of $l_1, \ldots, l_{k_1-1}$, at least one literal from $(l_i^{01}, l_{i+1}^0, \ldots, l_{k_1}^0)$ is not satisfied by $M$, which by the contraposition of the induction hypothesis $(b)$ proves that $l_{k_1}^0 = l_{k_1}$ is not satisfied by $M$. This means that $M$ satisfies $l_{k_1}$. □

Lemma 6
Let $w_1$ and $w_2$ be some types in $\{cla, sup, sta\}$.

Let $P_g$ be a $w_1$-enforcing set of p-conditions. Let $g$ be a generating function. Let $P_t$ be a $w_2$-enforcing set of p-conditions. Let $t$ be a witness function. Let $\Pi$ be a program. Then:

1. any terminal state of $STT_{P_g}^{P_t, g}(\Pi)$ reachable from the initial state and other than Failstate is $Ok(L)$, with $L$ being a $w_1$-model of $g(\Pi)$ such that $t(\Pi, L)$ has no $w_2$-model,

2. Failstate is reachable from the initial state iff $g(\Pi)$ has no $w_1$-model $L$ such that $t(\Pi, L)$ has no $w_2$-model.

Proof
We first illustrate that any terminal state is either Failstate or of the form $Ok(L)$ for some $L$. By contradiction. Assume there is a terminal state of the form $(L, R)_{\delta}$. Case 1. $s = L$. Then either a left rule or Cross$_{\mathcal{LR}}$ applies, so $(L, R)_{\delta}$ is not terminal. We derive a contradiction. Case 2. $s = R$. Since Conclude$_{\mathcal{RL}}$ does not apply while
no right-rule applies and no left-rule applies, L contains at least one decision literal. Since Backtrack$_{RL}$ is not applicable, L contains no decision literal. We derive a contradiction.

Statement 1. Let Ok(L) be a terminal state reachable from the initial state. As it is different from the initial state there is a transition leading to it. This transition can only be Conclude$_R$. Let us call (L,R), a state from which a transition Conclude$_R$ leads to Ok(L). By the definition of Conclude$_R$, we know that: s = R, that R is inconsistent and that R contains no decision literal. By Lemma 5 item (c), the consistent set of literals obtained from L is a w$_1$-model of g(II).

By Lemma 5 item (a), and as R contains no decision literal, any w$_2$-model of t(II, L) satisfies all the literals of R. Since R is inconsistent, any w$_2$-model of t(II, L) is inconsistent. So t(II, L) has no w$_2$-model.

We have just proved that L is a w$_1$-model of g(II) such that t(II, L) has no w$_2$-model.

Statement 2. Assume Failstate is not reachable from the initial state. Then, since the graph is acyclic, there is a terminal state different from Failstate. By Claim 1, this state is Ok(L), and L is a w$_1$-model of g(II) such that t(II, L) has no w$_2$-model.

Assume Failstate is reachable from the initial state. As it is different from the initial state there is a transition leading to it. This transition can only be Conclude$_L$ or Conclude$_{RL}$. Let us call (L,R), a state from which a transition leads to Failstate. In either of these cases, L does not contain any decision literal; so by Lemma 5, any w$_1$-model M of g(II) such that t(II, M) has no w$_2$-model satisfies all the literals of L. In other words, L is the only possible candidate for a w$_1$-model of g(II) such that t(II, L) has no w$_2$-model.

Case Conclude$_L$. It follows that L is inconsistent. Consequently, it is not a w$_1$-model M of g(II) such that t(II, L) has no w$_2$-model.

Case Conclude$_{RL}$. By Proposition 5 (d), the set of literals R is a w$_2$-model of t(II, L). Thus L is not a w$_1$-model of g(II) such that t(II, L) has no w$_2$-model.

Proof of Proposition 4

We first illustrate that any set M of literals that is a w$_1$-model of g(II) such that t(II, M) has no w$_2$-model is such that M$_{\text{atoms}(II)}$ is a stable model of II. Indeed, by the definition of w$_1$-approximating functions w.r.t. w, M$_{\text{atoms}(II)}$ is a w-model of II. Also, by the definition of w$_2$-ensuring functions w.r.t. w, M$_{\text{atoms}(II)}$ is a stable model of II.

Second, consider any stable model L of II. By the definitions of w$_1$-approximating and w$_2$-ensuring functions w.r.t. w, it follows there is M$'$ such that M$'_{\text{atoms}(II)}$ = L and M$'$ is a w$_1$-model of g(II) such that t(II, M$'$) has no w$_2$-model.
Proof of Theorem 4

Let $w_1$ denote a type such that $P_g$ is $w_1$-enforcing and the function $g$ is $w_1$-approximating w.r.t. $w$. Let $w_2$ denote a type such that $P_t$ is $w_2$-enforcing and function $t$ is $w_2$-ensuring w.r.t. $w$. We now proceed to prove the four conditions of the definition of ‘checks’ one by one.

1. By Lemma 4, the graph $STT_{P_g, t}^P(\Pi)$ is acyclic and finite.
2. By Lemma 6 item 1, any terminal state is either $\text{Failstate}$ or Ok($L$).
3. By Lemma 6 item 1, any terminal state of $STT_{P_g, t}^P(\Pi)$ reachable from the initial state and other than $\text{Failstate}$ is Ok($L$), with $L$ being a $w_1$-model of $g(\Pi)$ such that $t(\Pi, L)$ has no $w_2$-model. By Proposition 4, $L_{\{\text{atoms}(\Pi)\}}$ is a stable model of $\Pi$.
4. By Lemma 6 item 2, $\text{Failstate}$ is reachable from the initial state iff $g(\Pi)$ has no $w_1$-model $L$ such that $t(\Pi, L)$ has no $w_2$-model. By Proposition 4, $\Pi$ has no stable models.

Proof of Proposition 2

Recall how we argued $DP_{\Pi}$ is $\text{STT}_{up, cl}^P(\Pi)$. Similarly, $DP_{g,t}^2(\Pi)$ is $\text{STT}_{up, cl}^P(\Pi)$.

By Theorem 2, $up$ is $cl$-enforcing.

1. By Lemma 4, $DP_{g,t}^2(\Pi)$ is finite and acyclic.
2. By Lemma 6 item 1, any terminal state is either $\text{Failstate}$ or Ok($L$).
3. By Lemma 6 item 1, any terminal state of $STT_{P_g, t}^P(\Pi)$ reachable from the initial state and other than $\text{Failstate}$ is Ok($L$), with $L$ being a $cl$-model of $g(\Pi)$ such that $t(\Pi, L)$ has no $cl$-model.
4. By Lemma 6 item 2, $\text{Failstate}$ is reachable from the initial state iff $g(\Pi)$ has no $cl$-model $L$ such that $t(\Pi, L)$ has no $cl$-model.

6.3 Proof of Theorem 5

First we prove an auxiliary lemma that will help handling CNF conversions of DNF formulas.

For a DNF formula $F$, we define $CNF(F)$ as the conversion of $F$ to CNF using straightforward equivalent transformations: the distributivity of disjunction over conjunction.

Lemma 7

Let $F$ be a DNF formula. Let $l$ be a literal of $F$. Let $M$ be a set of literals.

The two following statements are equivalent:

1. there is a conjunctive clause $D$ of $F$ such that for every conjunctive clause $D' \in F$ different from $D$, $D'$ is contradicted by $M$,
2. there is a clause $C$ of $CNF(F)$ such that $l \in C$ and $M$ contradicts $C \setminus \{l\}$. 

Proof
Formula $F$ has the form $\bigvee_{i=1}^{n} \bigwedge_{j=1}^{k} l_{ij}$ (when necessary the true constant $\top$ is added multiple times to ensure that the conjunctive clauses of $F$ are of equal length). Also $\text{CNF}(F) = \bigwedge_{(k_1, \ldots, k_n) \in \{1, \ldots, k\}^n} \bigvee_{i=1}^{n} l_{ik_i}$.

From Statement 1 to Statement 2: Assume that there is a conjunctive clause $D$ of $F$ such that for any other conjunctive clause $D'$ of $F$, this clause is contradicted by $M$. Let $l$ be a literal of $D$. Let $D$ be $\bigwedge_{j=1}^{k} l_{ij}$ for some $i_0$. As any other conjunctive clause is contradicted by $M$, and as these clauses are conjunctions, there is least one literal of each of these clauses that is contradicted by $M$. Let us call $r_1 \ldots r_{i_0-1} r_{i_0+1} \ldots r_n$ these literals. Then for each $i \in \{1, \ldots, i_0 - 1, i_0 + 1, \ldots, n\}$, there is $k_i \in \{1, \ldots, k\}$ such that $l_{i,k_i} = r_i$. Also, there is some $k_{i_0}$ such that $l_{i_0,k_{i_0}} = l$. Then the clause $\bigvee_{i=1}^{n} l_{ik_i}$ of $\text{CNF}(F)$ contains $l$ while each of the other literals it contains is contradicted by $M$.

From Statement 2 to Statement 1: Assume that for some clause of $\text{CNF}(F)$, all literals but one are known to be contradicted by $M$. Then let this clause be $\bigvee_{i=1}^{n} l_{ik_i}$ for some $i$ and let $l_{i_0k_{i_0}}$ be the literal that is not contradicted by $M$. Then $l_{ik_i}$ is contradicted by $M$ for any $i$ other than $i_0$. So $\bigwedge_{j=1}^{k} l_{ij}$ is contradicted by $M$ for any $i$ other than $i_0$. So $D = \bigwedge_{j=1}^{k} l_{ij}$ is a conjunctive clause of $F$ such that for any other conjunctive clause $D'$ of $F$, this clause is contradicted by $M$.

Proof of Theorem 5
We must prove that for any edge in the graph $\text{STT}^{\text{sd}, g^D}_{\text{P}_1, t}(\Pi)$ there is an edge in $\text{STT}^{\text{up}, \text{cnfcomp}}_{\text{P}_1, t}(\Pi)$ linking two identical vertexes, and for any edge in the graph $\text{STT}^{\text{up}, \text{cnfcomp}}_{\text{P}_1, t}(\Pi)$ there is an edge in $\text{STT}^{\text{sd}, g^D}_{\text{P}_1, t}(\Pi)$ linking two identical vertexes.

If the edge is justified by a right-rule then this is obvious as these two graphs have the same witness function and the same set of conditions for the $\text{Propagate}_{\text{R}}$ rule. If the edge is $\text{Decide}_\mathcal{L}$, $\text{Conclude}_\mathcal{L}$, $\text{Backtrack}_\mathcal{L}$, $\text{Backtrack}_{\text{R} \mathcal{L}}$ or $\text{Conclude}_{\text{R} \mathcal{L}}$ then obviously there is the same edge in the other graph, bearing the same name, as these edges do not depend on the generating program or set of conditions for the $\text{Propagate}_{\text{R}}$ rule.

It remains to study the case of an edge justified by $\text{Propagate}_\mathcal{L}$ or $\text{Cross}_{\mathcal{L} \mathcal{R}}$. Assume we also have proved that $\text{Propagate}_\mathcal{L}$ rules are identical in both graphs. Then if an edge is justified by $\text{Cross}_{\mathcal{L} \mathcal{R}}$ in one of the graphs, which means that no left-rule applies in this graph, equivalently no left-rule applies in the other graph, and $\text{Cross}_{\mathcal{L} \mathcal{R}}$ also applies in that graph. We now show that $\text{Propagate}_\mathcal{L}$ rules are identical in both graphs, which will complete the proof.

Assume that an edge is justified by $\text{Propagate}_\mathcal{L}$ in one of the graphs, let us prove it also exists in the other graph.

A transition in $\text{STT}^{\text{sd}, g^D}_{\text{P}_1, t}(\Pi)$ is justified by $\text{Propagate}_\mathcal{L}$ with $\text{UnitPropagate}$ as condition. Then also there is an edge in $\text{STT}^{\text{up}, \text{cnfcomp}}_{\text{P}_1, t}(\Pi)$ with the same effect, and justified by $\text{Propagate}_\mathcal{L}$ with the $\text{UnitPropagate}$ condition. Indeed, $\Pi$ is part of $\text{cnfcomp}(\Pi)$. 

Disjunctive Answer Set Solvers via Templates
A transition in $\text{STT}^{sd,g^0} (\Pi)$ is justified by $\text{Propagate}_L$ with $\text{AllRulesCancelled}$ as condition. Then the edge is turning $(L, \emptyset)_L$ into $(L \neg a, \emptyset)_L$, and each rule $A \lor a \leftarrow B \in \Pi$ is not a supporting rule for $a$ w.r.t. $L$. In other words, for each rule $A \lor a \leftarrow B \in \Pi$ the following holds $L \cap (B \cup A) \neq \emptyset$. Consequently, the conjunction $B \land \overline{A}$ is contradicted by $L$. As a consequence $\bigwedge_{A \lor a \leftarrow B \in \Pi} (B \land \overline{A})$ is contradicted by $L$. From Lemma 7, the fact that the DNF formula $\neg a \lor \bigwedge_{A \lor a \leftarrow B \in \Pi} (B \land \overline{A})$ belongs to $\text{comp}(\Pi)$, and the $\text{cnfcomp}$ construction, it follows that there is a clause $C$ in $\text{cnfcomp}(\Pi)$ such that $\neg a \in C$ and $L$ contradicts $C \setminus \{\neg a\}$. So the rule $\text{Propagate}_L$ with condition $\text{UnitPropagate}$ of $\text{STT}^{ap,\text{cnfcomp}} (\Pi)$ can be applied to $C$ to add $\neg a$, providing the edge we needed.

A transition in $\text{STT}^{sd,g^0} (\Pi)$ is justified by $\text{Propagate}_L$ with $\text{BackchainTrue}$ as condition. The proof of this case is similar to the proof of previous case.

A transition in $\text{STT}^{ap,\text{cnfcomp}} (\Pi)$ is justified by $\text{Propagate}_L$ with the condition $\text{UnitPropagate}$. Let us call $F_0$ the DNF formula $\neg a \lor \bigwedge_{A \lor a \leftarrow B \in \Pi} (B \land \overline{A})$ of $\text{comp}(\Pi)$ for some atom $a$ in $\Pi$.

Case 1: $\text{Unit}_L$ is applied to a clause of $\Pi$ in $\text{cnfcomp}(\Pi)$. Then $\text{Propagate}_L$ with the condition $\text{UnitPropagate}$ itself provides the desired edge in $\text{STT}^{sd,g^0} (\Pi)$.

Case 2: $\text{Unit}_L$ is applied to a clause obtained from $F_0$ by the $\text{cnfcomp}$ conversion. Then by Lemma 7, the $\text{cnfcomp}$ construction, and the $\text{Unit}_L$ condition there is a conjunctive clause $D$ of $F_0$ such that for every conjunctive clause $D'$ in $F_0$ that is different from $D$ the current $L$ contradicts $D'$.

Case 2.1: This conjunctive clause is $\neg a$. Then $L$ contradicts $\bigwedge_{A \lor a \leftarrow B \in \Pi} (B \land \overline{A})$. It is easy to see that $\text{AllRulesCancelled}$ provides the desired edge.

Case 2.2: This conjunctive clause is some $B \land \overline{A}$. Then $L$ contradicts $\neg a$ so $a \in L$. Also $L$ contradicts all of $(B' \land \overline{A'} | A' \lor a \leftarrow B' \in \Pi \setminus \{A \lor a \leftarrow B\})$. As a consequence $\text{BackchainTrue}$ provides the desired edge. □

7 Conclusions, Future and Related Work

Transition systems for describing DPLL-based solving procedures have been introduced by Nieuwenhuis et al. (2006). Lierler (2008) introduced and compared the transition systems for the answer set solvers SMODELS and CMODELS for non-disjunctive programs. In this paper, we continue this direction of work by presenting a two-layer framework suitable to capture disjunctive answer set solvers. We argue that this framework allows simpler analysis and comparison of these systems. We first introduce a general template that includes the techniques implemented in such solvers, and then define specific solvers by instantiating appropriate techniques using this template. Formal results about the correctness of the abstract representations are given. We believe that this work is a stepping stone towards clear, comprehensive articulation of main design features of current disjunctive answer set solvers that will inspire new solving algorithms. Section 5 hints at some of
the possibilities. Indeed, to obtain a new solver one can combine any appropriately chosen approximating-pair and ensuring-pair.

Nieuwenhuis et al. (2006) considered another extension of the graphs by introducing transition rules that capture backjumping and learning techniques common in design of modern solvers, that later allowed Lierler (2011) to design, e.g., abstract CLASP. It is a direction of future work to extend the two-layer template graph to model such advances solving techniques. This extension will allow us to model disjunctive answer set solvers that rely heavily on backjumping and learning such as CLASP and WASP.

Related work. The approach based on transition systems for describing and comparing ASP procedures is one of the three main alternatives studied in the ASP literature. Other methods include pseudo-code presentation of algorithms (Giunchiglia and Maratea 2005; Giunchiglia et al. 2008) and tableau calculi (Gebser and Schaub 2006; Gebser and Schaub 2013). Giunchiglia et al. (2008) presented pseudo-code descriptions of CMODELS without backjumping and learning, SMODELS and DLV without backjumping restricted to non-disjunctive programs. They study relationships to the solving algorithms by analyzing the correspondence about the search spaces they explore, focusing on tight programs: in particular, they note a tight relation between solvers CMODELS and DLV. Gebser and Schaub (2013) considered formal proof systems based on tableau methods for characterizing the operations and the strategies of ASP procedures for disjunctive programs. These proof systems also allow cardinality constraints in the language of logic programs.

References


