

Decision Procedures

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DPLL(T)

Suppose we have a $T_{\mathbb{Q}}$ -formulae that is not conjunctive:

$$(x \geq 0 \rightarrow y > z) \wedge (x + y \geq z \rightarrow y \leq z) \wedge (y \geq 0 \rightarrow x \geq 0) \wedge x + y \geq z$$

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Is there a more efficient way to prove unsatisfiability?

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Converting to CNF and restricting to \leq :

$$\begin{aligned} &(\neg(0 \leq x) \vee \neg(y \leq z)) \wedge (\neg(z \leq x + y) \vee (y \leq z)) \\ &\quad \wedge (\neg(0 \leq y) \vee (0 \leq x)) \wedge (z \leq x + y) \end{aligned}$$

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Now, introduce boolean variables for each atom:

$$P_1 : 0 \leq x$$

$$P_2 : y \leq z$$

$$P_3 : z \leq x + y$$

$$P_4 : 0 \leq y$$

Gives a propositional formula:

$$(\neg P_1 \vee \neg P_2) \wedge (\neg P_3 \vee P_2) \wedge (\neg P_4 \vee P_1) \wedge P_3$$

The core feature of the DPLL-algorithm is Unit Propagation.

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$$P_1 : 0 \leq x$$

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$$P_3 : z \leq x + y$$

$$P_4 : 0 \leq y$$

This gives the **conjunctive** T_Q -formula

$$z \leq x + y \wedge y \leq z \wedge x < 0 \wedge y < 0.$$

We describe DPLL(T) by a set of rules modifying a configuration.
A configuration is a triple

$$\langle M, F, C \rangle,$$

where

- M (model) is a sequence of literals (that are currently set to true) interspersed with backtracking points denoted by \square .
- F (formula) is a formula in CNF, i. e., a set of clauses where each clause is a set of literals.
- C (conflict) is either \top or a conflict clause (a set of literals). A conflict clause C is a clause with $F \Rightarrow C$ and $M \not\models C$. Thus, a conflict clause shows $M \not\models F$.

We describe the algorithm by a set of rules, which each describe a set of transitions between configurations, e. g.,

Explain $\frac{\langle M, F, C \cup \{l\} \rangle}{\langle M, F, C \cup \{l_1, \dots, l_k\} \rangle}$ where $l \notin C$, $\{l_1, \dots, l_k, \bar{l}\} \in F$,
and $\bar{l}_1, \dots, \bar{l}_k \prec \bar{l}$ in M .

Here, $\bar{l}_1, \dots, \bar{l}_k \prec \bar{l}$ in M means the literals $\bar{l}_1, \dots, \bar{l}_k$ occur in the sequence M before the literal \bar{l} (and all literals appear in M).

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Example: for $M = P_1 \bar{P}_3 \bar{P}_2 \bar{P}_4$, $F = \{\{P_1\}, \{P_3, \bar{P}_4\}\}$, and $C = \{P_2\}$ the transition

$$\langle M, F, \{P_2, P_4\} \rangle \longrightarrow \langle M, F, \{P_2, P_3\} \rangle$$

is possible.

Decide $\frac{\langle M, F, \top \rangle}{\langle M \cdot \square \cdot \ell, F, \top \rangle}$

where $\ell \in \text{lit}(F)$, $\ell, \bar{\ell}$ in M

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$$\text{Propagate} \quad \frac{\langle M, F, \top \rangle}{\langle M \cdot \ell, F, \top \rangle}$$

where $\{l_1, \dots, l_k, \ell\} \in F$
and $\bar{l}_1, \dots, \bar{l}_k$ in M , $\ell, \bar{\ell}$ in M .

$$\text{Decide} \quad \frac{\langle M, F, \top \rangle}{\langle M \cdot \square \cdot l, F, \top \rangle}$$

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$$\text{Conflict} \quad \frac{\langle M, F, \top \rangle}{\langle M, F, \{l_1, \dots, l_k\} \rangle}$$

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$$\text{Explain} \quad \frac{\langle M, F, C \cup \{l\} \rangle}{\langle M, F, C \cup \{l_1, \dots, l_k\} \rangle}$$

where $l \notin C$, $\{l_1, \dots, l_k, \bar{l}\} \in F$,
and $\bar{l}_1, \dots, \bar{l}_k < \bar{l}$ in M .

$$\text{Decide } \frac{\langle M, F, \top \rangle}{\langle M \cdot \square \cdot \ell, F, \top \rangle}$$

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and $\bar{l}_1, \dots, \bar{l}_k \prec \bar{\ell}$ in M .

$$\text{Learn } \frac{\langle M, F, C \rangle}{\langle M, F \cup \{C\}, C \rangle}$$

where $C \neq \top$, $C \notin F$.

$$\text{Decide } \frac{\langle M, F, \top \rangle}{\langle M \cdot \square \cdot l, F, \top \rangle}$$

where $l \in \text{lit}(F)$, $l, \bar{l} \notin M$

$$\text{Propagate } \frac{\langle M, F, \top \rangle}{\langle M \cdot l, F, \top \rangle}$$

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$$\text{Learn } \frac{\langle M, F, C \rangle}{\langle M, F \cup \{C\}, C \rangle}$$

where $C \neq \top$, $C \notin F$.

$$\text{Back } \frac{\langle M, F, \{l_1, \dots, l_k, l\} \rangle}{\langle M' \cdot l, F, \top \rangle}$$

where $\{l_1, \dots, l_k, l\} \in F$,
 $M = M' \cdot \square \dots \bar{l} \dots$,
and $\bar{l}_1, \dots, \bar{l}_k \in M'$.

$$P_1 \wedge (\neg P_2 \vee P_3) \wedge (\neg P_4 \vee P_3) \wedge (P_2 \vee P_4) \wedge (\neg P_1 \vee \neg P_4 \vee \neg P_3) \wedge (P_4 \vee \neg P_3)$$

The algorithm starts with $M = \epsilon$, $C = \top$ and

$$F = \{\{P_1\}, \{\bar{P}_2, P_3\}, \{\bar{P}_4, P_3\}, \{P_2, P_4\}, \{\bar{P}_1, \bar{P}_4, \bar{P}_3\}, \{P_4, \bar{P}_3\}\}.$$

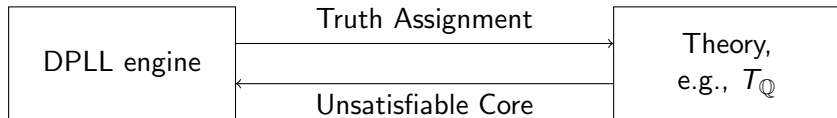
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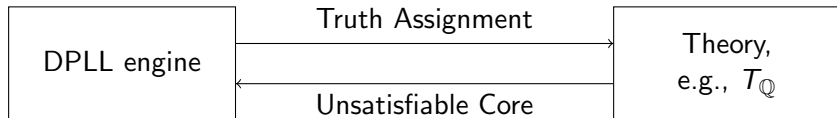
$$\begin{aligned} &\langle \epsilon, F, \top \rangle \xrightarrow{\text{Propagate}} \langle P_1, F, \top \rangle \xrightarrow{\text{Decide}} \langle P_1 \square \bar{P}_2, F, \top \rangle \xrightarrow{\text{Propagate}} \\ &\langle P_1 \square \bar{P}_2 P_4, F, \top \rangle \xrightarrow{\text{Propagate}} \langle P_1 \square \bar{P}_2 P_4 P_3, F, \top \rangle \xrightarrow{\text{Conflict}} \\ &\langle P_1 \square \bar{P}_2 P_4 P_3, F, \{\bar{P}_1, \bar{P}_4, \bar{P}_3\} \rangle \xrightarrow{\text{Explain}} \langle P_1 \square \bar{P}_2 P_4 P_3, F, \{\bar{P}_1, \bar{P}_4\} \rangle \xrightarrow{\text{Learn}} \\ &\langle P_1 \square \bar{P}_2 P_4 P_3, F', \{\bar{P}_1, \bar{P}_4\} \rangle \xrightarrow{\text{Back}} \langle P_1 \bar{P}_4, F', \top \rangle \xrightarrow{\text{Propagate}} \\ &\langle P_1 \bar{P}_4 P_2 P_3, F', \top \rangle \xrightarrow{\text{Conflict}} \langle P_1 \bar{P}_4 P_2 P_3, F', \{P_4, \bar{P}_3\} \rangle \xrightarrow{\text{Explain}} \\ &\langle P_1 \bar{P}_4 P_2 P_3, F', \{P_4, \bar{P}_2\} \rangle \xrightarrow{\text{Explain}} \langle P_1 \bar{P}_4 P_2 P_3, F', \{P_4\} \rangle \xrightarrow{\text{Explain}} \\ &\langle P_1 \bar{P}_4 P_2 P_3, F', \{\bar{P}_1\} \rangle \xrightarrow{\text{Explain}} \langle P_1 \bar{P}_4 P_2 P_3, F', \emptyset \rangle \xrightarrow{\text{Learn}} \\ &\langle P_1 \bar{P}_4 P_2 P_3, F' \cup \{\emptyset\}, \emptyset \rangle \end{aligned}$$

where $F' = F \cup \{\{\bar{P}_1, \bar{P}_4\}\}$.

The DPLL/CDCL algorithm is combined with a Decision Procedures for a Theory



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DPLL takes the **propositional core** of a formula, assigns truth-values to **atoms**.

Theory takes a **conjunctive** formula (conjunction of literals), returns a **minimal unsatisfiable core**.

Suppose we have a decision procedure for a conjunctive theory, e.g., Simplex Algorithm for $T_{\mathbb{Q}}$.

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- For each subset of **UnsatCore** the conjunction is satisfiable.

Possible approach: check for each literal whether it can be omitted.

→ n calls to decision procedure.

Most decision procedures can give small unsatisfiable cores for free.

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Thus the negation of an unsatisfiable core is a conflict clause.

The DPLL part only needs one new rule:

TConflict $\frac{\langle M, F, \top \rangle}{\langle M, F, C \rangle}$ where M is unsatisfiable in the theory
and $\neg C$ an unsatisfiable core of M .

$$F : y \geq 1 \wedge (x \geq 0 \rightarrow y \leq 0) \wedge (x \leq 1 \rightarrow y \leq 0)$$

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Atomic propositions:

$$P_1 : y \geq 1$$

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Propositional core of F in CNF:

$$F_0 : (P_1) \wedge (\neg P_2 \vee P_3) \wedge (\neg P_4 \vee P_3)$$

$$F_0 : \{ \{P_1\}, \{\bar{P}_2, P_3\}, \{\bar{P}_4, P_3\} \}$$
$$P_1 : y \geq 1 \quad P_2 : x \geq 0 \quad P_3 : y \leq 0 \quad P_4 : x \leq 1$$

Running DPLL(T)

$$F_0 : \{ \{P_1\}, \{\bar{P}_2, P_3\}, \{\bar{P}_4, P_3\} \}$$

$$P_1 : y \geq 1 \quad P_2 : x \geq 0 \quad P_3 : y \leq 0 \quad P_4 : x \leq 1$$

$$\begin{aligned} &\langle \epsilon, F_0, \top \rangle \xrightarrow{\text{Propagate}} \langle P_1, F_0, \top \rangle \xrightarrow{\text{Decide}} \langle P_1 \square P_3, F_0, \top \rangle \xrightarrow{\text{TConflict}} \\ &\langle P_1 \square P_3, F_0, \{\bar{P}_1, \bar{P}_3\} \rangle \xrightarrow{\text{Learn}} \langle P_1 \square P_3, F_1, \{\bar{P}_1, \bar{P}_3\} \rangle \xrightarrow{\text{Back}} \\ &\langle P_1 \bar{P}_3, F_1, \top \rangle \xrightarrow{\text{Propagate}} \langle P_1 \bar{P}_3 \bar{P}_2, F_1, \top \rangle \xrightarrow{\text{Propagate}} \\ &\langle P_1 \bar{P}_3 \bar{P}_2 \bar{P}_4, F_1, \top \rangle \xrightarrow{\text{TConflict}} \langle P_1 \bar{P}_3 \bar{P}_2 \bar{P}_4, F_1, \{P_2, P_4\} \rangle \xrightarrow{\text{Explain}} \\ &\langle P_1 \bar{P}_3 \bar{P}_2 \bar{P}_4, F_1, \{P_2, P_3\} \rangle \xrightarrow{\text{Explain}} \langle P_1 \bar{P}_3 \bar{P}_2 \bar{P}_4, F_1, \{P_3\} \rangle \xrightarrow{\text{Explain}} \\ &\langle P_1 \bar{P}_3 \bar{P}_2 \bar{P}_4, F_1, \{\bar{P}_1\} \rangle \xrightarrow{\text{Explain}} \langle P_1 \bar{P}_3 \bar{P}_2 \bar{P}_4, F_1, \emptyset \rangle \xrightarrow{\text{Learn}} \\ &\langle P_1 \bar{P}_3 \bar{P}_2 \bar{P}_4, F_1 \cup \{\emptyset\}, \emptyset \rangle \end{aligned}$$

$$\text{where } F_1 := F_0 \cup \{ \{ \bar{P}_1, \bar{P}_3 \} \}$$

No further step is possible; the formula F is unsatisfiable.

Theorem (Correctness of DPLL(T))

Let F be a Σ -formula and F' its propositional core. Let

$$\langle \epsilon, F', \top \rangle = \langle M_0, F_0, C_0 \rangle \longrightarrow \dots \longrightarrow \langle M_n, F_n, C_n \rangle$$

be a maximal sequence of rule application of DPLL(T).

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- C_i is always implied by F_i (or the theory).

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$$\langle \epsilon, F', \top \rangle = \langle M_0, F_0, C_0 \rangle \longrightarrow \dots \longrightarrow \langle M_n, F_n, C_n \rangle$$

be a maximal sequence of rule application of DPLL(T).

Then F is T -satisfiable iff C_n is \top .

Before proving the theorem, we note some important invariants:

- M_i never contains a literal more than once.
- M_i never contains ℓ and $\bar{\ell}$.
- Every \square in M_i is followed immediately by a literal.
- If $C_i = \{\ell_1, \dots, \ell_k\}$ then $\bar{\ell}_1, \dots, \bar{\ell}_k$ in M_i .
- C_i is always implied by F_i (or the theory).
- F is equivalent to F_i for all steps i of the computation.

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- If $C_i = \{\ell_1, \dots, \ell_k\}$ then $\bar{\ell}_1, \dots, \bar{\ell}_k$ in M .
- C_i is always implied by F_i (or the theory).
- F is equivalent to F_i for all steps i of the computation.
- If a literal ℓ in M is not immediately preceded by \square , then F contains a clause $\{\ell, \ell_1, \dots, \ell_k\}$ and $\bar{\ell}_1, \dots, \bar{\ell}_k \prec \ell$ in M .

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Assume $C_n = \{\bar{l}_1, \dots, \bar{l}_k, l\} \neq \emptyset$. W.l.o.g., $\bar{l}_1, \dots, \bar{l}_k \prec l$. Then:

- Since **Learn** is not applicable, $C_n \in F_n$.

Proof: If the sequence ends with $\langle M_n, F_n, \top \rangle$ and there is no rule applicable, then:

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- Since **Learn** is not applicable, $C_n \in F_n$.
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- However, then **Back** is applicable, contradiction!

Correctness proof

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If the sequence ends with $\langle M_n, F_n, C_n \rangle$ with $C_n \neq \top$.

Assume $C_n = \{\bar{l}_1, \dots, \bar{l}_k, l\} \neq \emptyset$. W.l.o.g., $\bar{l}_1, \dots, \bar{l}_k \prec l$. Then:

- Since **Learn** is not applicable, $C_n \in F_n$.
- Since **Explain** is not applicable \bar{l} must be immediately preceded by \square .
- However, then **Back** is applicable, contradiction!

Therefore, the assumption was wrong and $C_n = \emptyset (= \perp)$.

Since F implies C_n , F is not satisfiable.

Theorem (Termination of DPLL)

Let F be a propositional formula. Then every sequence

$$\langle \epsilon, F, \top \rangle = \langle M_0, F_0, C_0 \rangle \longrightarrow \langle M_1, F_1, C_1 \rangle \longrightarrow \dots$$

terminates.

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- We define $M \prec M'$ if $M \square \square$ comes lexicographically before $M' \square \square$, where every literal is considered to be smaller than \square .

Example: $l_1 l_2(\square \square) \prec l_1 \square \bar{l}_2 l_3(\square \square) \prec l_1 \square \bar{l}_2(\square \square) \prec l_1(\square \square)$

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- For a sequence $M = \bar{l}_1 \dots \bar{l}_n$, the conflict clauses are ordered by:

$C \prec_M C'$, iff $C \neq \top$, $C' = \top$ or for some $k \leq n$:

$C \cap \{l_{k+1}, \dots, l_n\} = C' \cap \{l_{k+1}, \dots, l_n\}$ and $l_k \notin C, l_k \in C'$.

Example: $\emptyset \prec_{\bar{l}_1 \bar{l}_2 \bar{l}_3} \{l_2\} \prec_{\bar{l}_1 \bar{l}_2 \bar{l}_3} \{l_1, l_3\} \prec_{\bar{l}_1 \bar{l}_2 \bar{l}_3} \{l_2, l_3\} \prec_{\bar{l}_1 \bar{l}_2 \bar{l}_3} \top$

These are **well-orderings**, because the domains are finite.

Proof of Total Correctness

We define some well-ordering on the domains:

- We define $M \prec M'$ if $M \square \square$ comes lexicographically before $M' \square \square$, where every literal is considered to be smaller than \square .

Example: $l_1 l_2(\square \square) \prec l_1 \square \bar{l}_2 l_3(\square \square) \prec l_1 \square \bar{l}_2(\square \square) \prec l_1(\square \square)$

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These are **well-orderings**, because the domains are finite.

Termination Proof: Every rule application decreases the value of $\langle M_i, F_i, C_i \rangle$ according to the well-ordering:

$$\langle M, F, C \rangle \prec \langle M', F', C' \rangle, \text{ iff } \begin{cases} M \prec M', \\ \text{or } M = M', C \prec_M C', \\ \text{or } M = M', C = C', C \in F, C \notin F'. \end{cases}$$