Exploitation of dynamic symmetries for solving SAT problems

Doctorat de Sorbonne Université

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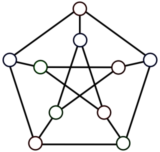
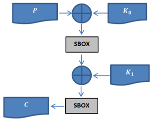
Motivation

Graph coloring

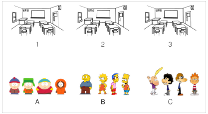


Cryptanalysis



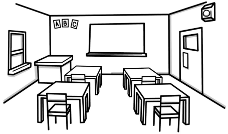
Hardware verification

Planning

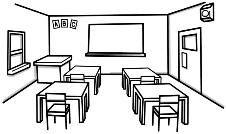


Boolean SATisfiability

SAT: an example (1/2)



1



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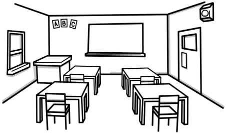
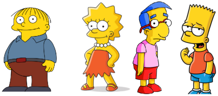
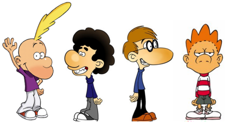


3

A



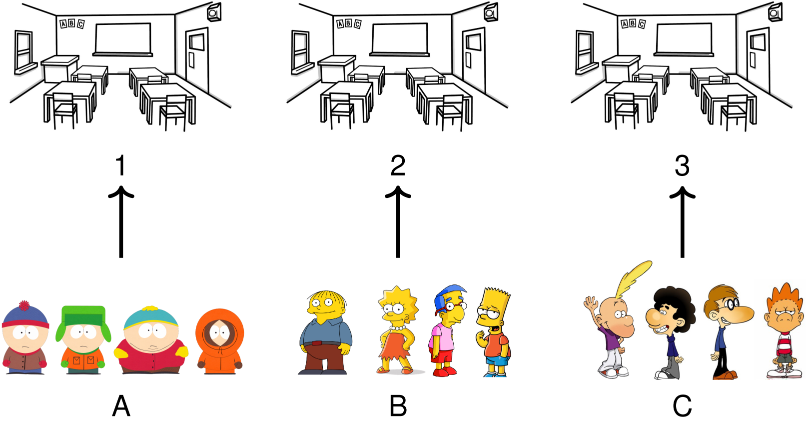
B



C

Is it possible to attribute each group to a unique classroom?

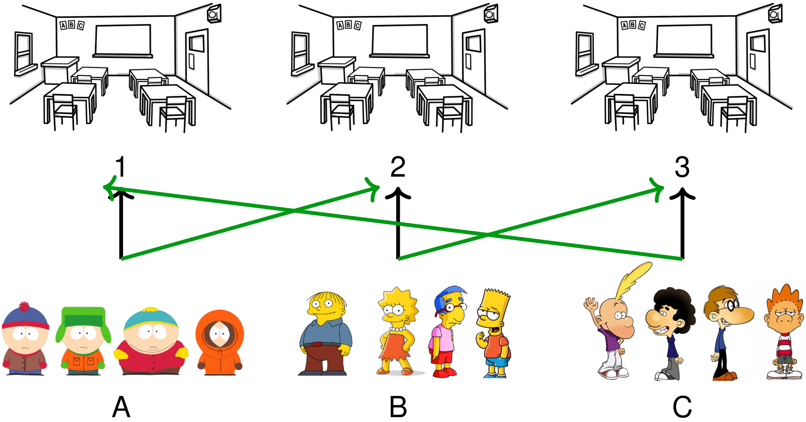
SAT: an example (1/2)



Is it possible to attribute each group to a unique classroom?

YES! $\texttt{SAT}$isfiable $\alpha = (A, 1), (B, 2), (C, 3)$

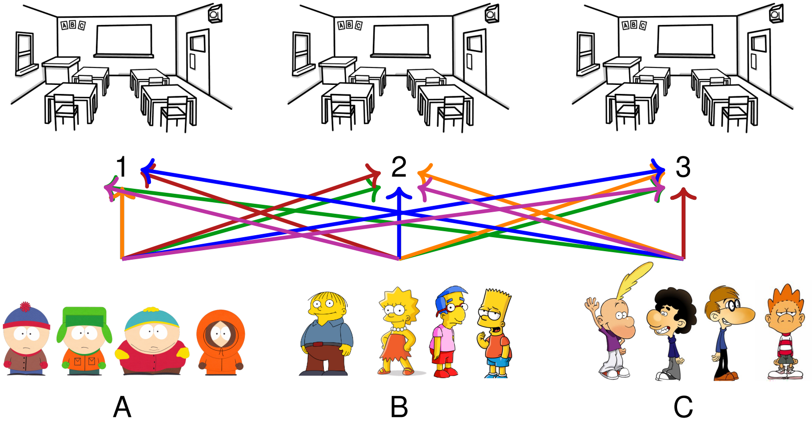
SAT: an example (1/2)



Is it possible to attribute each group to a unique classroom?

YES! $\texttt{SAT}$isfiable $\alpha = (A, 1), (B, 2), (C, 3)$
Many solutions $\alpha' = (A, 2), (B, 3), (C, 1)$

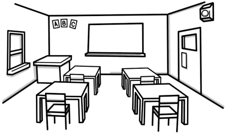
SAT: an example (1/2)



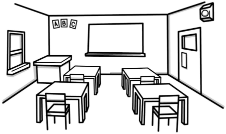
Is it possible to attribute each group to a unique classroom?

YES! SATisfiable $\alpha = (A, 1), (B, 2), (C, 3)$
Many solutions $\alpha' = (A, 2), (B, 3), (C, 1)$
$\alpha'' = \cdots$

SAT: an example (2/2)

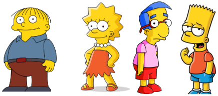


1

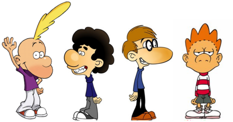


2

A



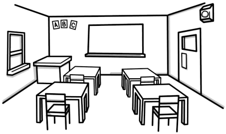
B

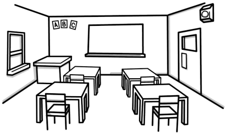


C

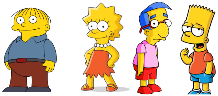
Is it possible to attribute each group to a unique classroom?

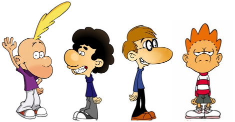
SAT: an example (2/2)


1


2


A

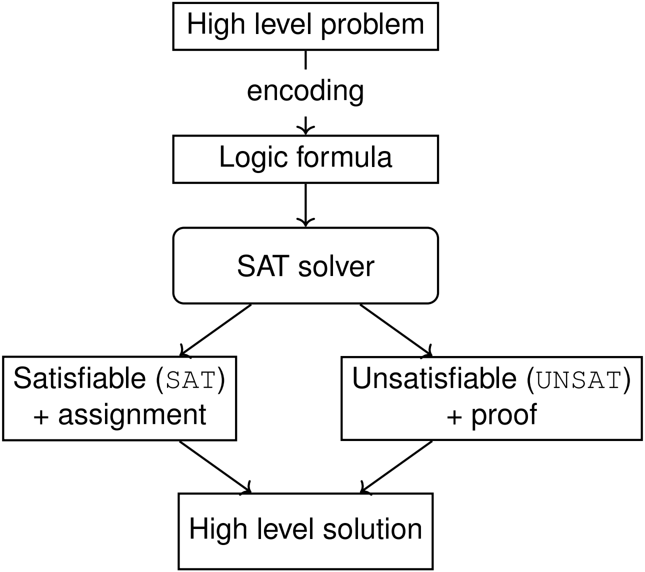

B


C

Is it possible to attribute each group to a unique classroom?

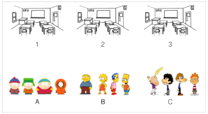
No! `UNSAT`isfiable

From high level problem to the solution through SAT solving



Encoding the problem

$$\begin{array}{ccc} \overbrace{(A,1)}^{x_1} & \overbrace{(A,2)}^{x_2} & \overbrace{(A,3)}^{x_3} \\ (B,1) & (B,2) & (B,3) \\ (C,1) & (C,2) & (C,3) \end{array}$$

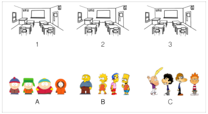


$$\begin{array}{l} (x_1 \vee x_2 \vee x_3) \ \wedge \\ (x_4 \vee x_5 \vee x_6) \ \wedge \\ (x_7 \vee x_8 \vee x_9) \ \wedge \end{array}$$

Encoding the problem

$$\overbrace{(A,1)}^{x_1}\overbrace{(A,2)}^{x_2}\overbrace{(A,3)}^{x_3}$$
$$(B,1)(B,2)(B,3)$$
$$(C,1)(C,2)(C,3)$$

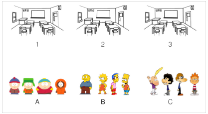
$$\neg(A,1)\neg(B,1)$$
$$\neg(A,1)\neg(C,1)$$
$$\neg(B,1)\neg(C,1)$$



$$(x_1 \vee x_2 \vee x_3) \quad \wedge$$
$$(x_4 \vee x_5 \vee x_6) \quad \wedge$$
$$(x_7 \vee x_8 \vee x_9) \quad \wedge$$

$$(\neg x_1 \vee \neg x_4) \quad \wedge$$
$$(\neg x_1 \vee \neg x_7) \quad \wedge$$
$$(\neg x_4 \vee \neg x_7) \quad \wedge$$

Encoding the problem



$$\overbrace{(A,1)}^{x_1}\overbrace{(A,2)}^{x_2}\overbrace{(A,3)}^{x_3}$$
$$(B,1)(B,2)(B,3)$$
$$(C,1)(C,2)(C,3)$$

$$\neg(A,1)\neg(B,1)$$
$$\neg(A,1)\neg(C,1)$$
$$\neg(B,1)\neg(C,1)$$

$$\neg(A,2)\neg(B,2)$$
$$\neg(A,2)\neg(C,2)$$
$$\neg(B,2)\neg(C,2)$$

$$\neg(A,3)\neg(B,3)$$
$$\neg(A,3)\neg(C,3)$$
$$\neg(B,3)\neg(C,3)$$

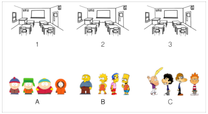
$$(x_1 \vee x_2 \vee x_3) \;\wedge$$
$$(x_4 \vee x_5 \vee x_6) \;\wedge$$
$$(x_7 \vee x_8 \vee x_9) \;\wedge$$

$$(\neg x_1 \vee \neg x_4) \;\wedge$$
$$(\neg x_1 \vee \neg x_7) \;\wedge$$
$$(\neg x_4 \vee \neg x_7) \;\wedge$$

$$(\neg x_2 \vee \neg x_5) \;\wedge$$
$$(\neg x_2 \vee \neg x_8) \;\wedge$$
$$(\neg x_5 \vee \neg x_8) \;\wedge$$

$$(\neg x_3 \vee \neg x_6) \;\wedge$$
$$(\neg x_3 \vee \neg x_9) \;\wedge$$
$$(\neg x_6 \vee \neg x_9)$$

Encoding the problem



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$$\neg(A,2)\neg(B,2)$$
$$\neg(A,2)\neg(C,2)$$
$$\neg(B,2)\neg(C,2)$$

$$\neg(A,3)\neg(B,3)$$
$$\neg(A,3)\neg(C,3)$$
$$\neg(B,3)\neg(C,3)$$

Clause

$$\boxed{(x_1 \vee x_2 \vee x_3)} \wedge$$
$$(x_4 \vee x_5 \vee x_6) \wedge$$
$$(x_7 \vee x_8 \vee x_9) \wedge$$

$$(\neg x_1 \vee \neg x_4) \wedge$$
$$(\neg x_1 \vee \neg x_7) \wedge$$
$$(\neg x_4 \vee \neg x_7) \wedge$$

$$(\neg x_2 \vee \neg x_5) \wedge$$
$$(\neg x_2 \vee \neg x_8) \wedge$$
$$(\neg x_5 \vee \neg x_8) \wedge$$

$$(\neg x_3 \vee \neg x_6) \wedge$$
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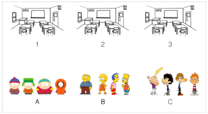
Encoding the problem



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$$\neg(A,2)\neg(B,2)$$
$$\neg(A,2)\neg(C,2)$$
$$\neg(B,2)\neg(C,2)$$

$$\neg(A,3)\neg(B,3)$$
$$\neg(A,3)\neg(C,3)$$
$$\neg(B,3)\neg(C,3)$$

Clause

$$\boxed{(x_1 \vee x_2 \vee x_3)} \wedge$$
$$(x_4 \vee x_5 \vee x_6) \wedge$$
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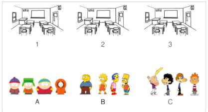
$$(\neg x_1 \vee \neg x_4) \wedge$$
$$(\neg x_1 \vee \neg x_7) \wedge$$
$$(\neg x_4 \vee \neg x_7) \wedge$$

$$(\neg x_2 \vee \neg x_5) \wedge$$
$$(\neg x_2 \vee \neg x_8) \wedge$$
$$(\neg x_5 \vee \neg x_8) \wedge$$

$$(\neg x_3 \vee \neg x_6) \wedge$$
$$(\neg x_3 \vee \neg x_9) \wedge$$
$$(\neg x_6 \vee \neg x_9)$$

Conjunctive Normal Form (CNF)

Encoding the problem



$$\overbrace{(A,1)}^{x_1}\overbrace{(A,2)}^{x_2}\overbrace{(A,3)}^{x_3}$$
$$(B,1)(B,2)(B,3)$$
$$(C,1)(C,2)(C,3)$$

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$$\neg(B,1)\neg(C,1)$$

$$\neg(A,2)\neg(B,2)$$
$$\neg(A,2)\neg(C,2)$$
$$\neg(B,2)\neg(C,2)$$

$$\neg(A,3)\neg(B,3)$$
$$\neg(A,3)\neg(C,3)$$
$$\neg(B,3)\neg(C,3)$$

Clause

$$\boxed{(x_1 \vee x_2 \vee x_3)} \wedge$$
$$(x_4 \vee x_5 \vee x_6) \wedge$$
$$(x_7 \vee x_8 \vee x_9) \wedge$$

$$(\neg x_1 \vee \neg x_4) \wedge$$
$$(\neg x_1 \vee \neg x_7) \wedge$$
$$(\neg x_4 \vee \neg x_7) \wedge$$

$$(\neg x_2 \vee \neg x_5) \wedge$$
$$(\neg x_2 \vee \neg x_8) \wedge$$
$$(\neg x_5 \vee \neg x_8) \wedge$$

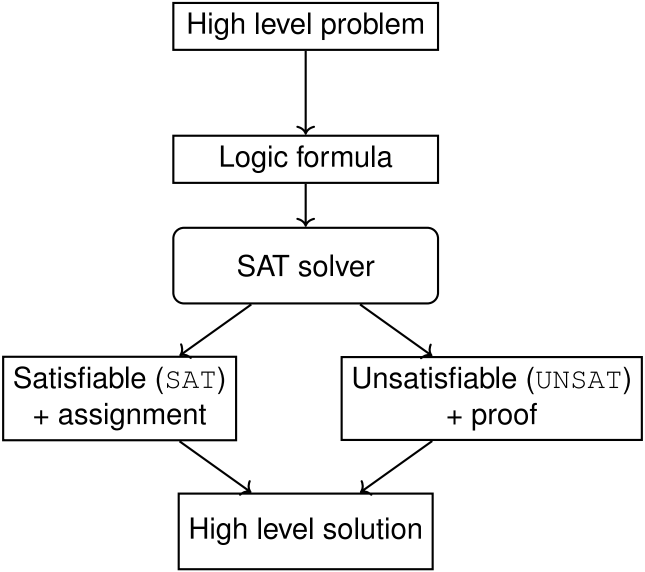
$$(\neg x_3 \vee \neg x_6) \wedge$$
$$(\neg x_3 \vee \neg x_9) \wedge$$
$$(\neg x_6 \vee \neg x_9)$$

Conjunctive Normal Form (CNF)

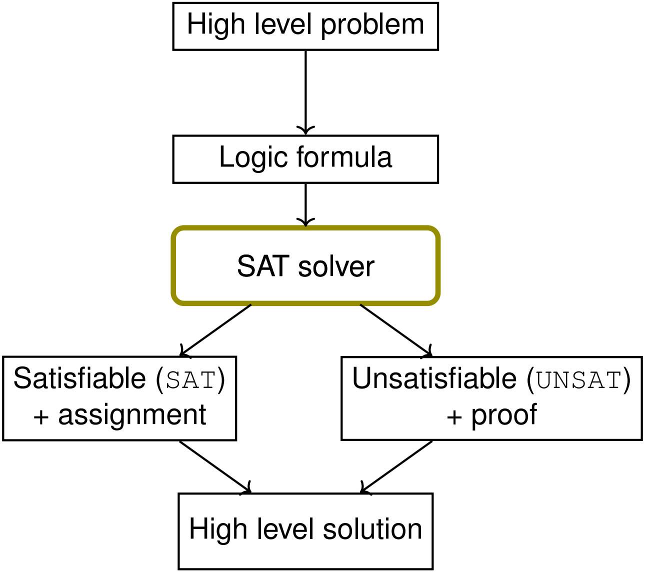
Clause represented as a set:

$$(x_1 \vee x_2 \vee x_3) \rightarrow \{x_1, x_2, x_3\}$$

From high level problem to the solution through SAT solving



From high level problem to the solution through SAT solving



SAT Solving

Solving SAT formula is known to be **NP-complete** [Coo71]

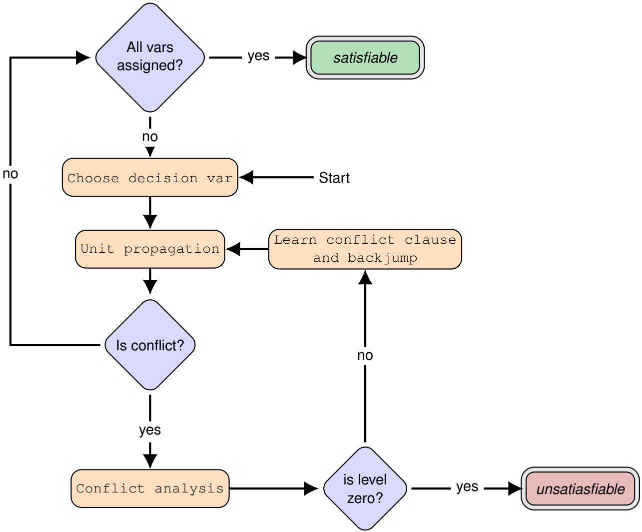
Good performance in practice:

- Handle large problem (million variables and clauses)
- International SAT competition each year on academic and industrial problems

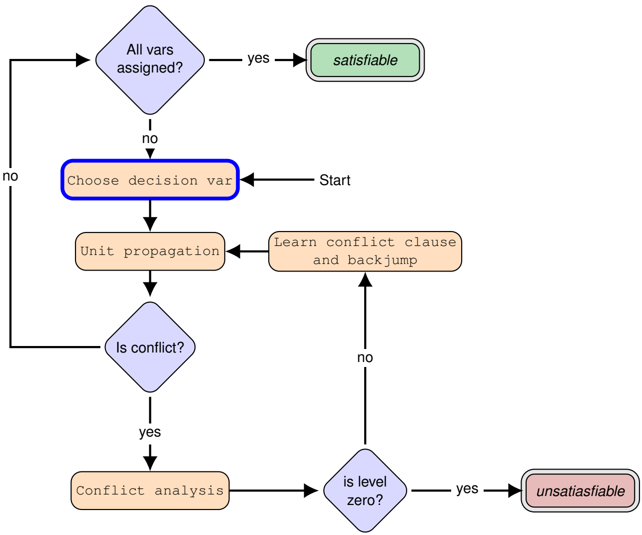
Enumerative algorithms:

- Davis, Putnam, Logemann, and Loveland (DPLL) [DLL62]
  - Boolean Constraint Propagation (BCP)
- **Conflict Driven Clause Learning** (CDCL) [MSS99]
  - Derived from DPLL
  - Clause learning

CDCL in detail



CDCL in detail



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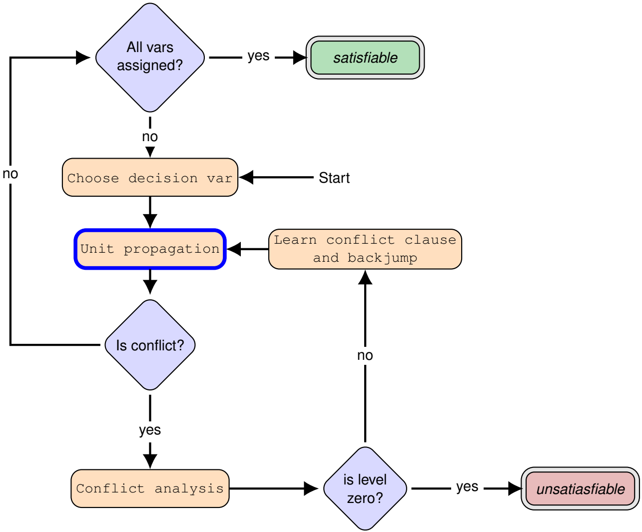

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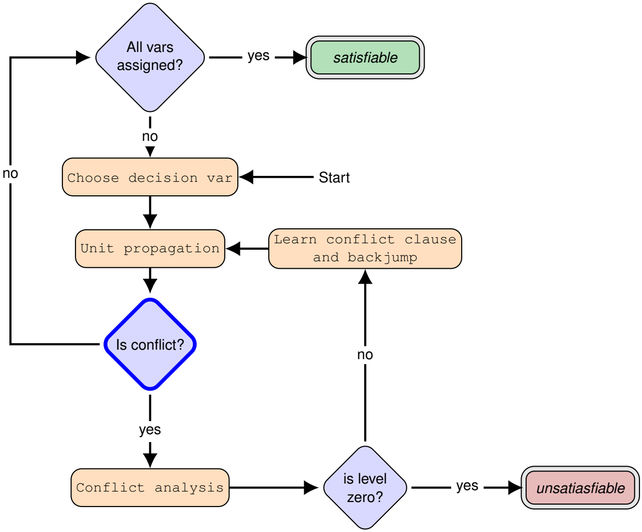

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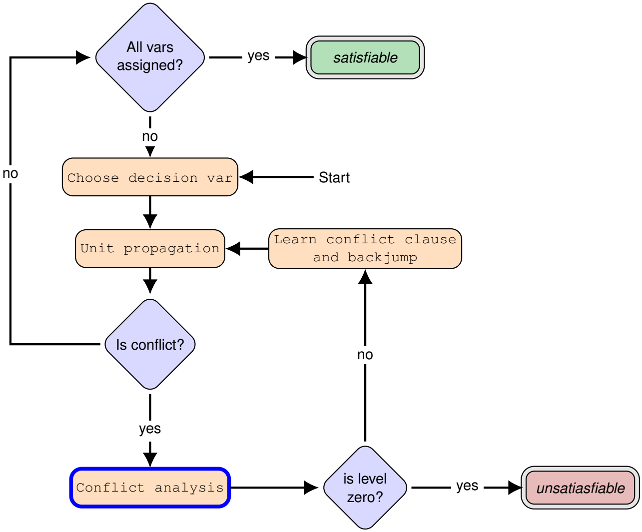

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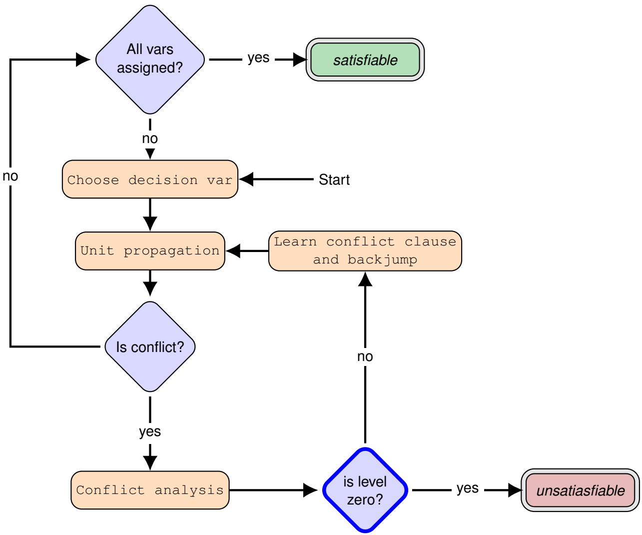

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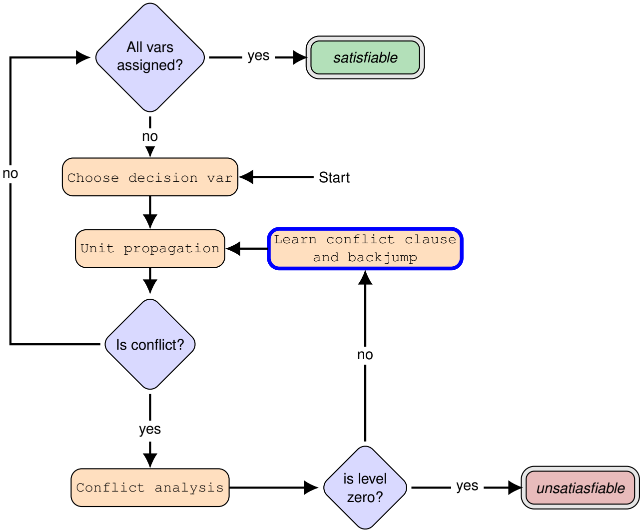

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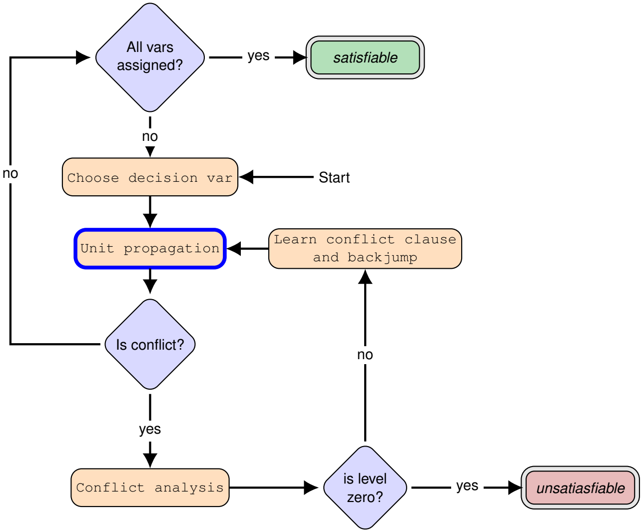

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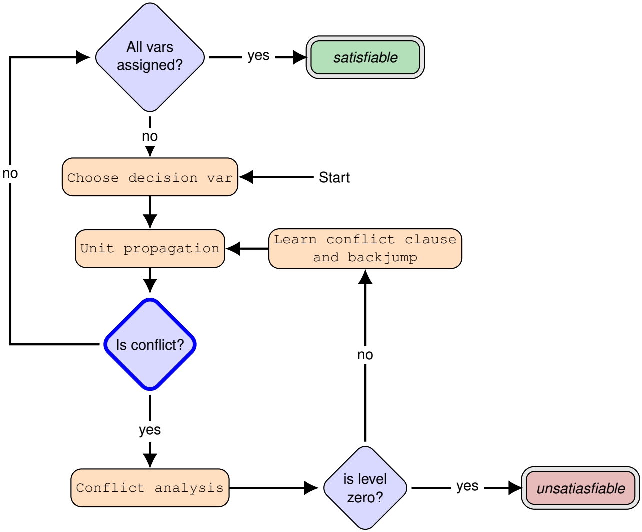

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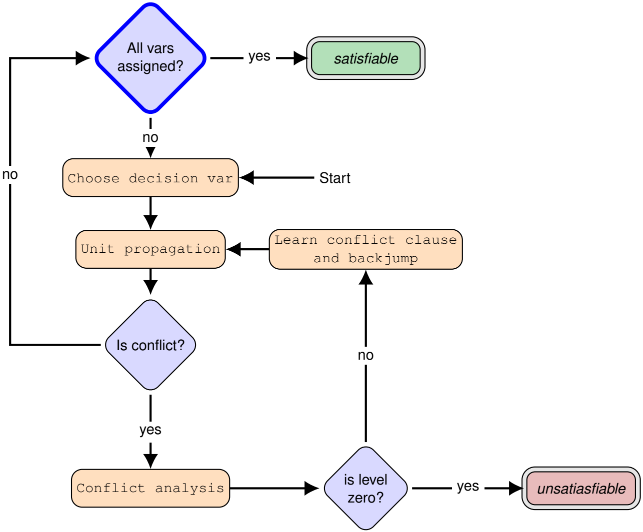

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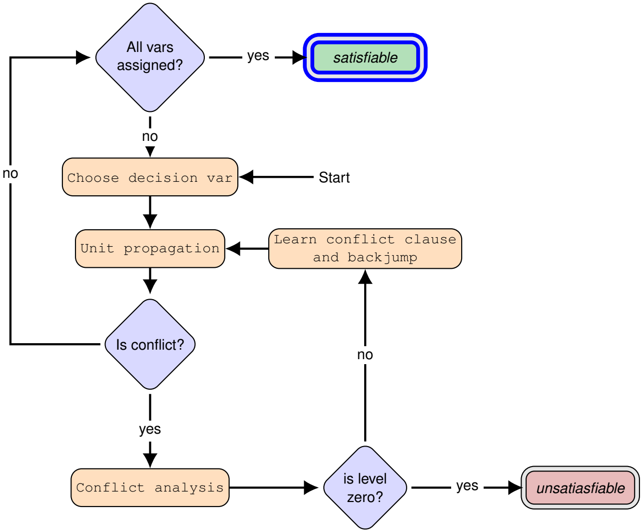
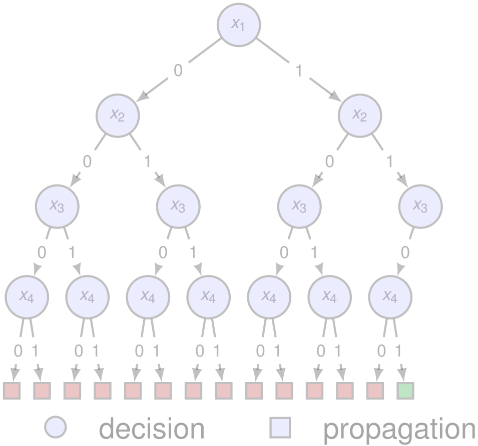


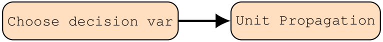
CDCL in action

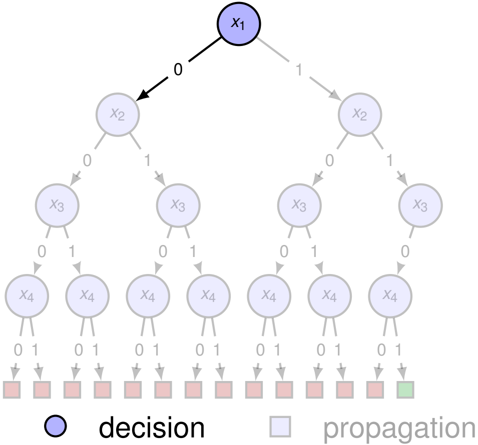


$$\omega_1 = \{x_1, x_2, x_3, x_4\}$$
$$\omega_2 = \{x_1, \neg x_4\}$$
$$\omega_3 = \{x_1, x_4\}$$
$$\omega_4 = \{x_2, \neg x_4\}$$
$$\omega_5 = \{x_2, x_4\}$$
$$\omega_6 = \{x_3, x_4\}$$

$$\alpha = \{\}$$

CDCL in action





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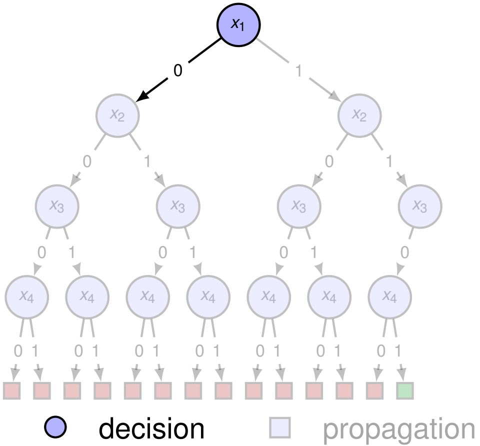
$$\omega_6 = \{x_3, x_4\}$$

$$\alpha = \{\neg x_1\}$$

CDCL in action

Conflict Analysis



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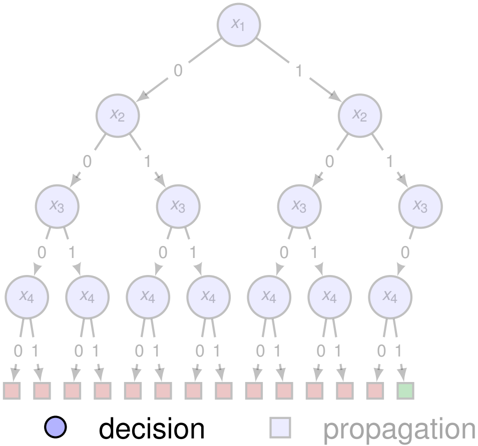
$$\alpha = \{\neg x_1\}$$

CDCL in action

Learn conflict clause and backjump

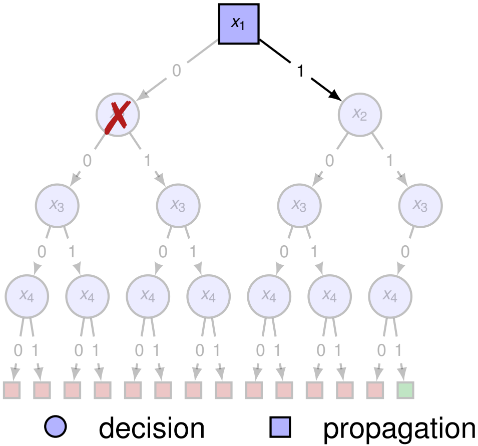


$$\omega_1 = \{x_1, x_2, x_3, x_4\}$$
$$\omega_2 = \{x_1, \neg x_4\}$$
$$\omega_3 = \{x_1, x_4\}$$
$$\omega_4 = \{x_2, \neg x_4\}$$
$$\omega_5 = \{x_2, x_4\}$$
$$\omega_6 = \{x_3, x_4\}$$
$$\omega_7 = \{x_1\}$$

$$\alpha = \{\}$$

CDCL in action

Unit Propagation



$$\omega_1 = \{x_1, x_2, x_3, x_4\}$$
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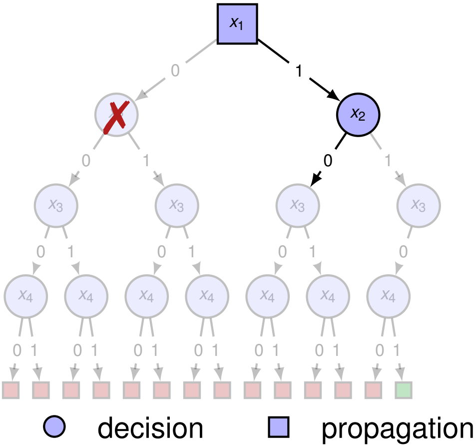
$$\omega_6 = \{x_3, x_4\}$$
$$\omega_7 = \{x_1\}$$

$$\alpha = \{x_1\}$$

CDCL in action

Choose decision var → Unit Propagation



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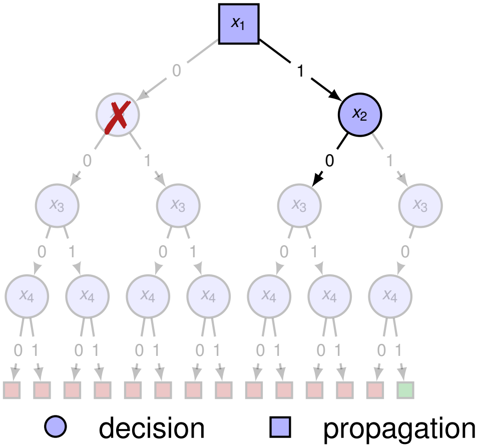
$$\omega_5 = \{x_2, x_4\}$$
$$\omega_6 = \{x_3, x_4\}$$
$$\omega_7 = \{x_1\}$$

$$\alpha = \{x_1, \neg x_2\}$$

CDCL in action

Conflict Analysis



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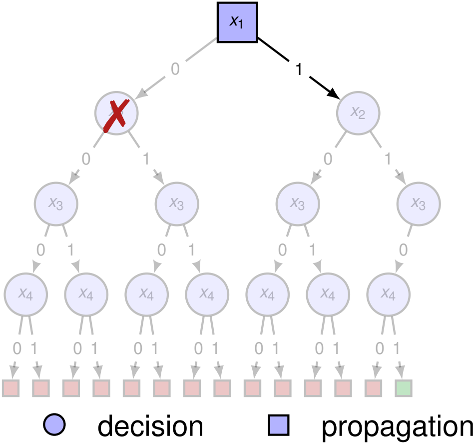
$$\omega_7 = \{x_1\}$$

$$\alpha = \{x_1, \neg x_2\}$$

CDCL in action

Learn conflict clause and backjump



$$\omega_1 = \{x_1, x_2, x_3, x_4\}$$
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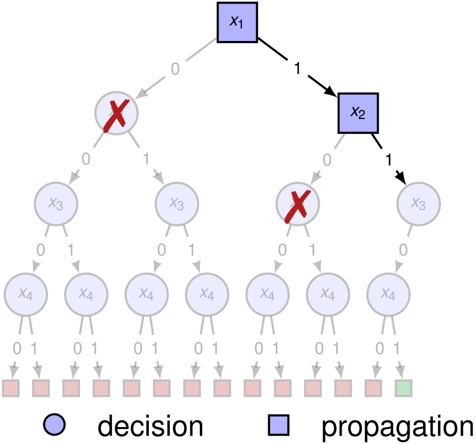
$$\omega_4 = \{x_2, \neg x_4\}$$
$$\omega_5 = \{x_2, x_4\}$$
$$\omega_6 = \{x_3, x_4\}$$
$$\omega_7 = \{x_1\}$$
$$\omega_8 = \{x_2\}$$

$$\alpha = \{x_1\}$$

CDCL in action

Unit Propagation



$$\omega_1 = \{x_1, x_2, x_3, x_4\}$$
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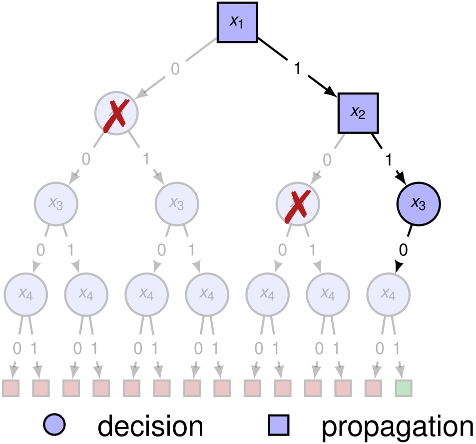
$$\omega_8 = \{x_2\}$$

$$\alpha = \{x_1, x_2\}$$

CDCL in action

Choose decision var → Unit Propagation



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$\omega_6 = \{x_3, x_4\}$

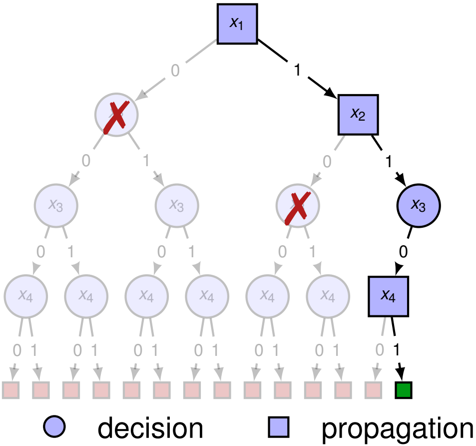
$\omega_7 = \{x_1\}$

$\omega_8 = \{x_2\}$

$$\alpha = \{x_1, x_2, \neg x_3\}$$

CDCL in action

satisfiable



$\omega_1 = \{x_1, x_2, x_3, x_4\}$

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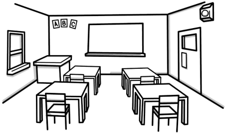
$\omega_8 = \{x_2\}$

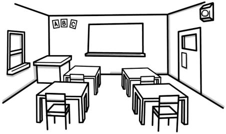
$$\alpha = \{x_1, x_2, \neg x_3, x_4\}$$

SAT and symmetries

Presence of symmetries

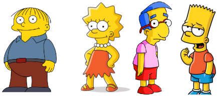


1

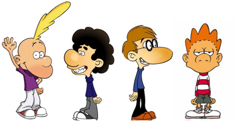


2

A

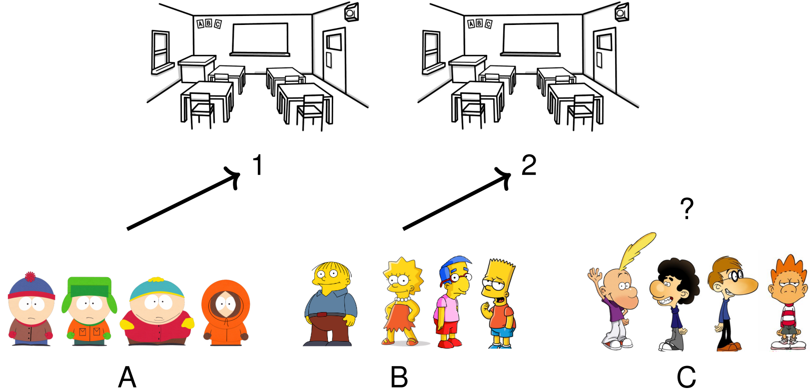


B

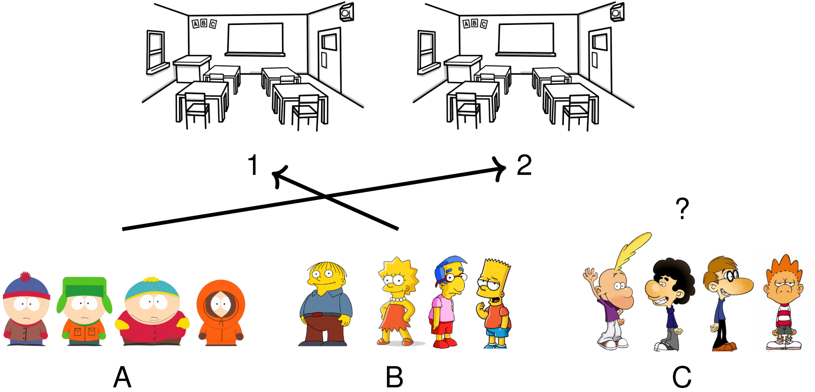


C

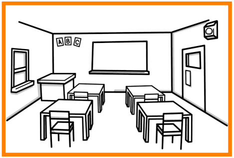
Presence of symmetries



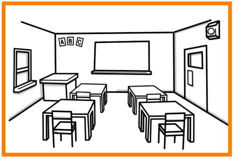
Presence of symmetries



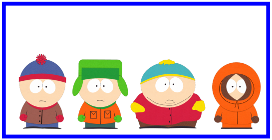
Presence of symmetries



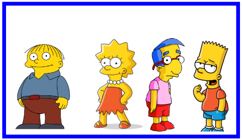
1



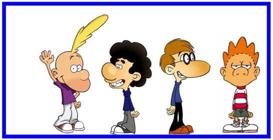
2



A

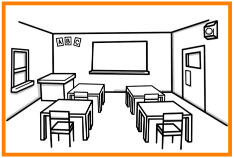


B

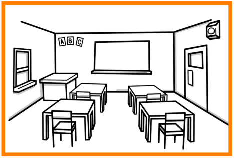


C

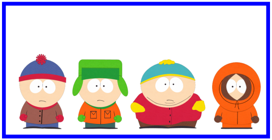
Presence of symmetries



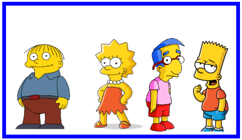
~~1~~ 2



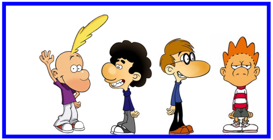
~~2~~ 1



A



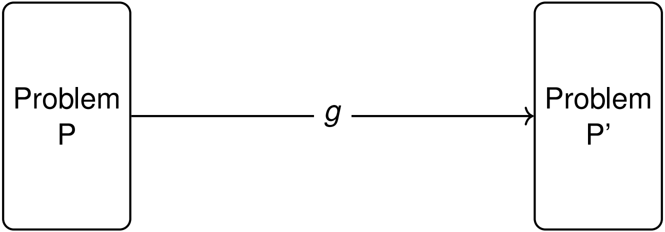
~~B~~ C



~~C~~ B

Symmetry in high level

Let g a symmetry



Symmetry in high level

Let g a symmetry

$$\boxed{\text{Problem P}} \xrightarrow{\quad g \quad} \boxed{\text{Problem P'}}$$

Equi-satisfiability

$$solution \models P \Leftrightarrow g.solution \models P'$$

Syntactic symmetry

A symmetry (permuation) g is a bijective function (on variables) that leaves the formula φ invariant

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A symmetry (permuation) g is a bijective function (on variables) that leaves the formula φ invariant

$$g = \begin{pmatrix} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 & x_9 \\ x_2 & x_1 & x_3 & x_5 & x_4 & x_6 & x_8 & x_7 & x_9 \end{pmatrix} \rightarrow (x_1 \ x_2)(x_4 \ x_5)(x_7 \ x_8)$$

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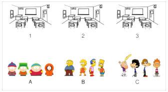
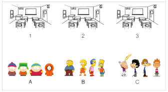


$$\begin{array}{lcl}
\omega_1 = \{x_1, x_2, x_3\} & \longleftrightarrow & \omega_1 = \{x_2, x_1, x_3\} \\
\omega_2 = \{x_4, x_5, x_6\} & \longleftrightarrow & \omega_2 = \{x_5, x_4, x_6\} \\
\omega_3 = \{x_7, x_8, x_9\} & \longleftrightarrow & \omega_3 = \{x_8, x_7, x_9\} \\
\omega_4 = \{\neg x_1, \neg x_4\} & & \omega_4 = \{\neg x_2, \neg x_5\} \\
\omega_5 = \{\neg x_1, \neg x_7\} & & \omega_5 = \{\neg x_2, \neg x_8\} \\
\omega_6 = \{\neg x_4, \neg x_7\} & & \omega_6 = \{\neg x_5, \neg x_8\} \\
\omega_7 = \{\neg x_2, \neg x_5\} & & \omega_7 = \{\neg x_1, \neg x_4\} \\
\omega_8 = \{\neg x_2, \neg x_8\} & & \omega_8 = \{\neg x_1, \neg x_7\} \\
\omega_9 = \{\neg x_5, \neg x_8\} & & \omega_9 = \{\neg x_4, \neg x_7\} \\
\omega_{10} = \{\neg x_3, \neg x_6\} & \longleftrightarrow & \omega_{10} = \{\neg x_3, \neg x_6\} \\
\omega_{11} = \{\neg x_3, \neg x_9\} & \longleftrightarrow & \omega_{11} = \{\neg x_3, \neg x_9\} \\
\omega_{12} = \{\neg x_6, \neg x_9\} & \longleftrightarrow & \omega_{12} = \{\neg x_6, \neg x_9\}
\end{array}$$



Computing symmetries of a SAT problem

CNF formula

$$
\begin{aligned}
&(x_1 \lor x_2 \lor x_3) \land (x_4 \lor x_5 \lor x_6) \land (x_7 \lor x_8 \lor x_9) \\
&\land(\neg x_1 \lor \neg x_4) \land (\neg x_1 \lor \neg x_7) \land (\neg x_4 \lor \neg x_7) \\
&\land(\neg x_2 \lor \neg x_5) \land (\neg x_2 \lor \neg x_8) \land (\neg x_5 \lor \neg x_8) \\
&\land(\neg x_3 \lor \neg x_6) \land (\neg x_3 \lor \neg x_9) \land (\neg x_6 \lor \neg x_9)
\end{aligned}
$$

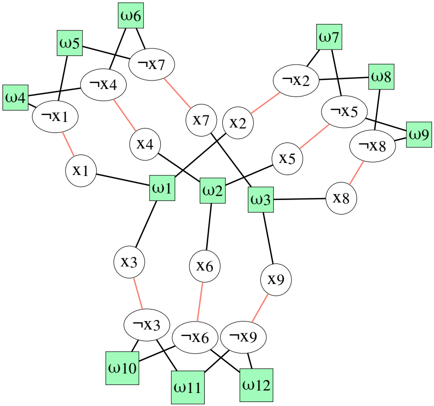
Computing symmetries of a SAT problem

CNF formula

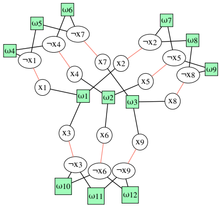
$$(x_1 \vee x_2 \vee x_3) \wedge (x_4 \vee x_5 \vee x_6) \wedge (x_7 \vee x_8 \vee x_9)$$
$$\wedge(\neg x_1 \vee \neg x_4) \wedge (\neg x_1 \vee \neg x_7) \wedge (\neg x_4 \vee \neg x_7)$$
$$\wedge(\neg x_2 \vee \neg x_5) \wedge (\neg x_2 \vee \neg x_8) \wedge (\neg x_5 \vee \neg x_8)$$
$$\wedge(\neg x_3 \vee \neg x_6) \wedge (\neg x_3 \vee \neg x_9) \wedge (\neg x_6 \vee \neg x_9)$$

$\Downarrow$ $\Downarrow$

colored graph



Computing symmetries of a SAT problem

CNF formula	$(x_1 \vee x_2 \vee x_3) \wedge (x_4 \vee x_5 \vee x_6) \wedge (x_7 \vee x_8 \vee x_9)$ $\wedge(\neg x_1 \vee \neg x_4) \wedge (\neg x_1 \vee \neg x_7) \wedge (\neg x_4 \vee \neg x_7)$ $\wedge(\neg x_2 \vee \neg x_5) \wedge (\neg x_2 \vee \neg x_8) \wedge (\neg x_5 \vee \neg x_8)$ $\wedge(\neg x_3 \vee \neg x_6) \wedge (\neg x_3 \vee \neg x_9) \wedge (\neg x_6 \vee \neg x_9)$
$\Downarrow$	$\Downarrow$
colored graph	
$\|$	$\|$
graph automorphism	(`bliss`, `saucy`, ...)

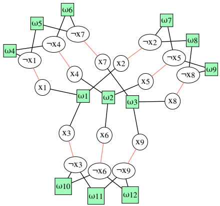
Computing symmetries of a SAT problem

CNF formula

$$(x_1 \vee x_2 \vee x_3) \wedge (x_4 \vee x_5 \vee x_6) \wedge (x_7 \vee x_8 \vee x_9)$$
$$\wedge(\neg x_1 \vee \neg x_4) \wedge (\neg x_1 \vee \neg x_7) \wedge (\neg x_4 \vee \neg x_7)$$
$$\wedge(\neg x_2 \vee \neg x_5) \wedge (\neg x_2 \vee \neg x_8) \wedge (\neg x_5 \vee \neg x_8)$$
$$\wedge(\neg x_3 \vee \neg x_6) \wedge (\neg x_3 \vee \neg x_9) \wedge (\neg x_6 \vee \neg x_9)$$

$\Downarrow$ $\Downarrow$

colored graph



$\|$ $\|$

graph automorphism

(`bliss`, `saucy`, ...)

$\Downarrow$ $\Downarrow$

set of symmetries

$$g_1 = (x_2 \;\; x_3)(x_5 \;\; x_6)(x_8 \;\; x_9)$$
$$g_2 = (x_4 \;\; x_7)(x_5 \;\; x_8)(x_6 \;\; x_9)$$
$$g_3 = (x_1 \;\; x_2)(x_4 \;\; x_5)(x_7 \;\; x_8)$$
$$g_4 = (x_1 \;\; x_4)(x_2 \;\; x_5)(x_3 \;\; x_6)$$

The set of symmetries of a formula is a group noted $< G, \circ >$

Exploitation of symmetries

Static symmetry breaking

Orbit

Orbit of an assignment α for a group G:

$$G.\alpha = \{g.\alpha \mid g \in G\}$$

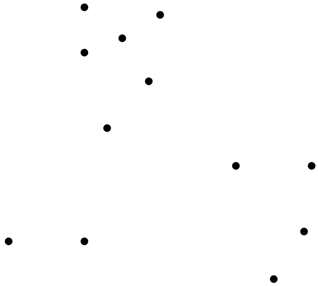
Orbit

Orbit of an assignment α for a group G:

$$G.\alpha = \{g.\alpha \mid g \in G\}$$

Example:

- full assignment



Orbit

Orbit of an assignment α for a group G:

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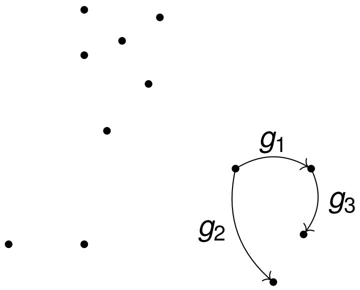
Example:

- full assignment



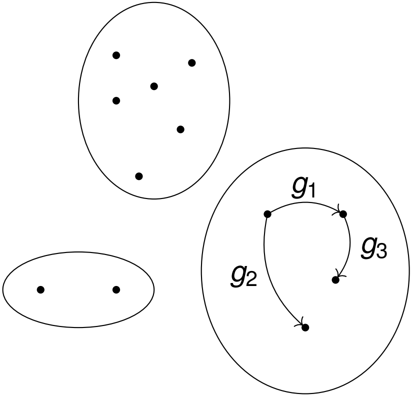
Orbit

Orbit of an assignment α for a group G:

$$G.\alpha = \{g.\alpha \mid g \in G\}$$

Example:

- full assignment
- orbit



Equivalence relation with respect to SAT:

- Either $G.\alpha$ contains no solution
- Or all elements of $G.\alpha$ are solutions

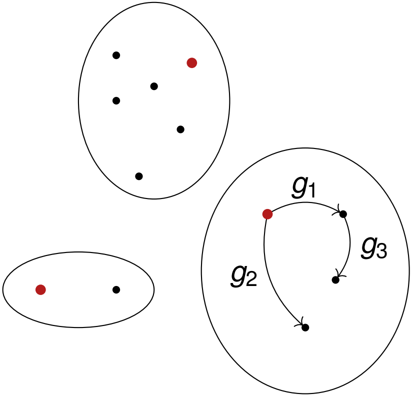
Orbit

Orbit of an assignment α for a group G:

$$G.\alpha = \{g.\alpha \mid g \in G\}$$

Example:

- full assignment
- orbit
- representative



Equivalence relation with respect to SAT:

- Either $G.\alpha$ contains no solution
- Or all elements of $G.\alpha$ are solutions

Comparing assignments (1/2)

Define an ordering relation to compare assignments ($\prec$)

- Total ordering on variables
- Minimum value: $\mathtt{F} < \mathtt{T}$ or $\mathtt{T} < \mathtt{F}$

Allow only minimal value (lex-leader)

Forbid other assignments in each orbit

$\rightarrow$ Add Symmetry breaking predicates (SBP)

Comparing assignments (2/2)

$x_1 \leq x_2 \leq x_3 \leq x_4 \leq x_5 \leq x_6 \leq x_7 \leq x_8; \mathtt{F} < \mathtt{T}$

$g = (x_1 \;\; x_2)(x_4 \;\; x_5)(x_7 \;\; x_8)$

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
α	T	F	F	F	F	F	F	F

Comparing assignments (2/2)

$x_1 \leq x_2 \leq x_3 \leq x_4 \leq x_5 \leq x_6 \leq x_7 \leq x_8; \mathtt{F} < \mathtt{T}$

$g = (x_1 \;\; x_2)(x_4 \;\; x_5)(x_7 \;\; x_8)$

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
α	T	F	F	F	F	F	F	F
$g.\alpha$	F	T	F	F	F	F	F	F

Comparing assignments (2/2)

$x_1 \leq x_2 \leq x_3 \leq x_4 \leq x_5 \leq x_6 \leq x_7 \leq x_8;\ \mathtt{F} < \mathtt{T}$

$g = (x_1\ \ x_2)(x_4\ \ x_5)(x_7\ \ x_8)$

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
α	T	F	F	F	F	F	F	F
$g.\alpha$	F	T	F	F	F	F	F	F

$g.\alpha \prec \alpha$

Comparing assignments (2/2)

$x_1 \le x_2 \le x_3 \le x_4 \le x_5 \le x_6 \le x_7 \le x_8$; $\mathtt{F} < \mathtt{T}$

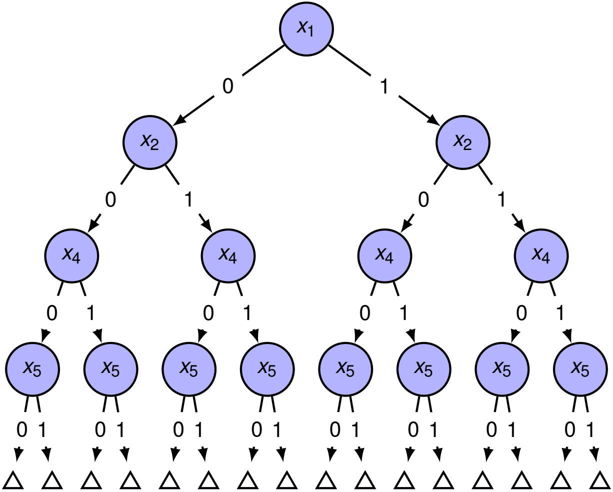
$g = (x_1 \;\; x_2)(x_4 \;\; x_5)(x_7 \;\; x_8)$

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
α	T	F	F	F	F	F	F	F
$g.\alpha$	F	T	F	F	F	F	F	F

$g.\alpha \prec \alpha \Rightarrow$ Generate SBP $\omega = \{\neg x_1, x_2\}$

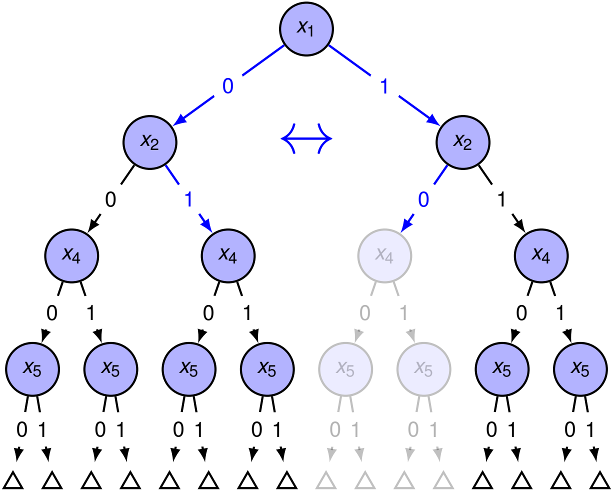
Using symmetries to prune the search space

$g = (x_1 \;\; x_2)(x_4 \;\; x_5)(x_7 \;\; x_8)$

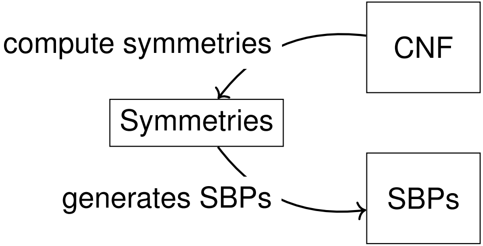


Using symmetries to prune the search space

$g = (x_1 \ \ x_2)(x_4 \ \ x_5)(x_7 \ \ x_8)$



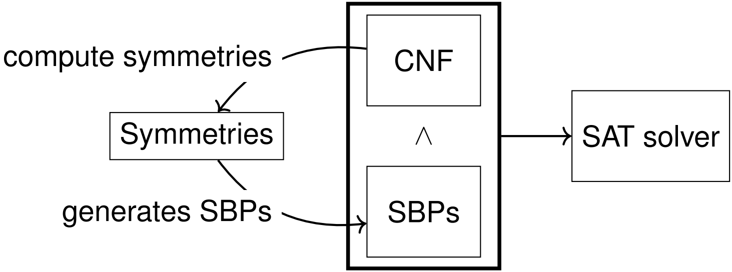
Static symmetry breaking



State-of-the-art approaches:

- Shatter [ASM06]
- BreakID [DBBD16]

Static symmetry breaking



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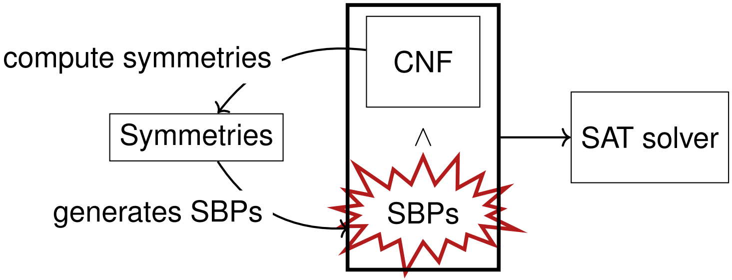


State-of-the-art approaches:

- Shatter [ASM06]
- BreakID [DBBD16]

The solver can ”explode” instead of being helped

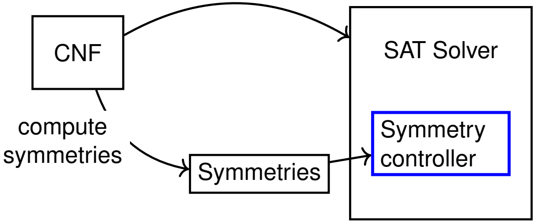
- generate not needed clause
- flooding the solver

First contribution

CDCL[sym] Introducing Effective Symmetry Breaking in SAT Solving

TACAS'18 [MBCK18]

General idea

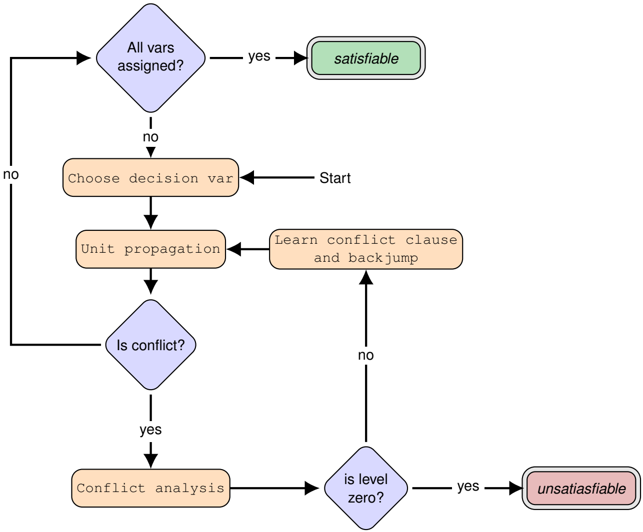


Symmetry controller:

- generates SBP on the fly
- only when needed
- intrusive on solver

CDCL[Sym]

Compute and inject SBP opportunistically, during the solving



CDCL[Sym]

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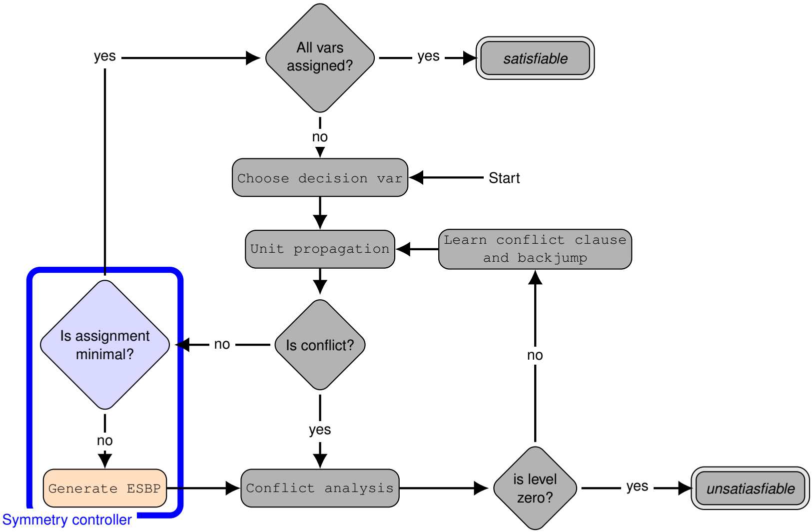

Is assignment minimal? Symmetry status

- `reducer`: $g.\alpha \prec \alpha$
- `inactive`: $\alpha \prec g.\alpha$
- `active`: *not enough information*

Is assignment minimal? Symmetry status

- `reducer`: $g.\alpha \prec \alpha$
- `inactive`: $\alpha \prec g.\alpha$
- `active`: *not enough information*

Efficient implementation of symmetry status

Keep track the smallest unassigned variable x:

1. $\alpha(g.x) \leq \alpha(x)$, then g is `reducer` $\Rightarrow$ Effective SBP (ESBP)
2. $\alpha(x) \leq \alpha(g.x)$, then g is `inactive` $\Rightarrow$ g cannot reduce α
3. $\alpha(g.x)$ or $\alpha(x)$ is unassigned then g is `active`

Example

$$x_1 \leq x_2 \leq x_3 \leq x_4 \leq x_5 \leq x_6 \leq x_7 \leq x_8; \mathtt{F} < \mathtt{T}$$

$$g = (x_1 \;\; x_2)(x_4 \;\; x_5)(x_7 \;\; x_8)$$

$$\downarrow$$

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
α	U	U	U	U	U	U	U	U
$g.\alpha$	U	U	U	U	U	U	U	U

$$g.\alpha \qquad \alpha$$

status of permutation g: `active`

Example

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α	T	F	U	F	U	U	U	U
$g.\alpha$	F	T	U	U	F	U	U	U

$$g.\alpha \prec \alpha$$

status of permutation g: `reducer`

Generate ESBP $\omega = \{\neg x_1, x_2\}$

CDCL[Sym] implementation

- C++ Implementation
- Packaged as a library **cosy**[1] (Controller of Symmetry)
- Lightweight
- Fast update
- Low memory consumption
- Follows symmetry status

- Works with any enumerative SAT solver
- Can be integrated easily

→ e.g. +3% LOC on `MiniSAT`[2].

[1] `https://github.com/lip6/cosy`
[2] 90 lines out of 3090

Experiments

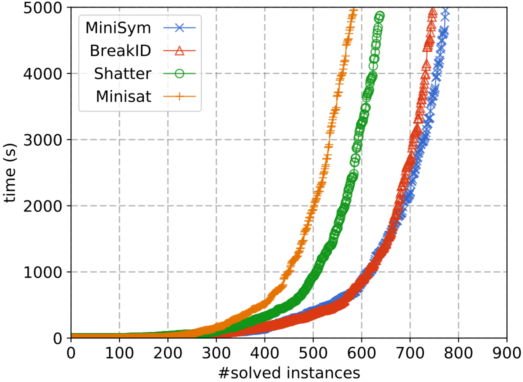
Benchmark:

- from SAT contests 2012 – 2017
- filter: `bliss` finds symmetries in 1000 seconds
- 36 % of instances, $1\,350/3\,700$

Setup:

- four tools
  - MiniSat (no symmetry, baseline)
  - MiniSat + BreakID (SOTA SAT solver using symmetries)
  - MiniSat + Shatter (SOTA SAT solver using symmetries)
  - **MiniSym** = MiniSat + CDCL[Sym] (our approach)
- 5000 seconds timeout, 8GB memory
- includes time to compute symmetries (except for MiniSat)

Experimental results



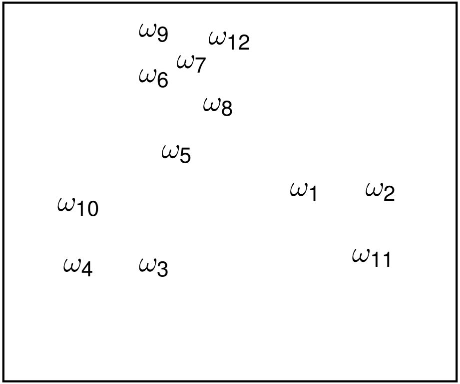
Solver	PAR-2	SAT	UNSAT
MiniSAT	2243h	325	261
Shatter	2088h	316	324
BreakID	1790h	334	415
MiniSym	**1735h**	**336**	**439**

Exploitation of symmetries

Dynamic symmetry breaking

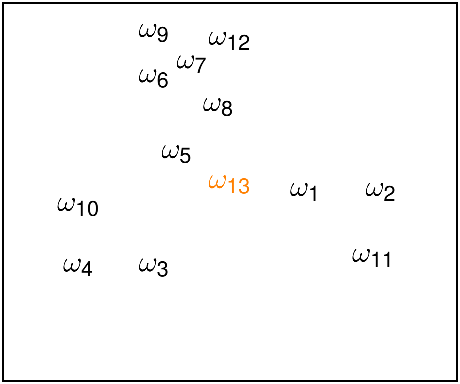
Learn symmetrical clauses

- □ formula
- ω clause



Learn symmetrical clauses

- $\square$ formula
- ω clause
- ω learnt clause



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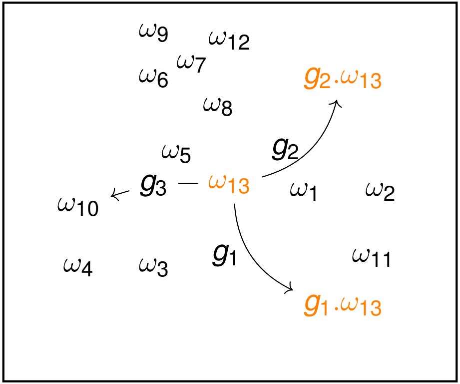
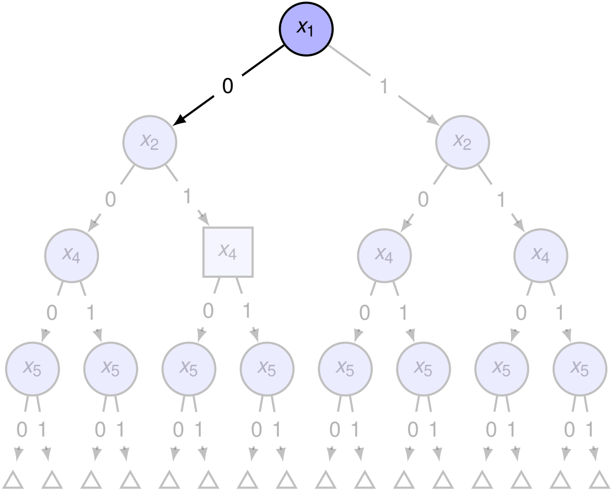


Using symmetries to accelerate the tree traversal

$g = (x_1 \;\; x_2)(x_4 \;\; x_5)(x_7 \;\; x_8)$



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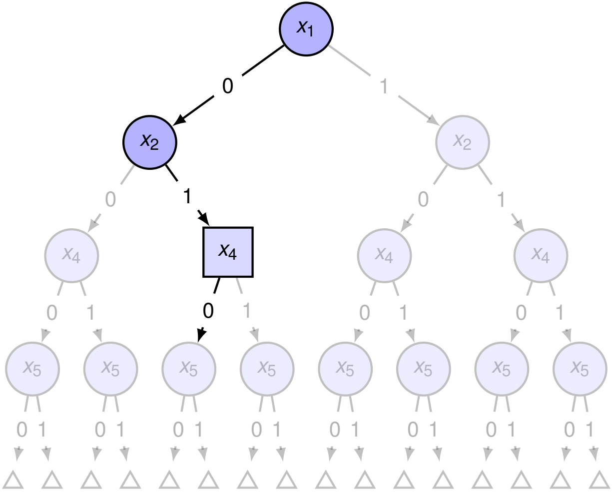

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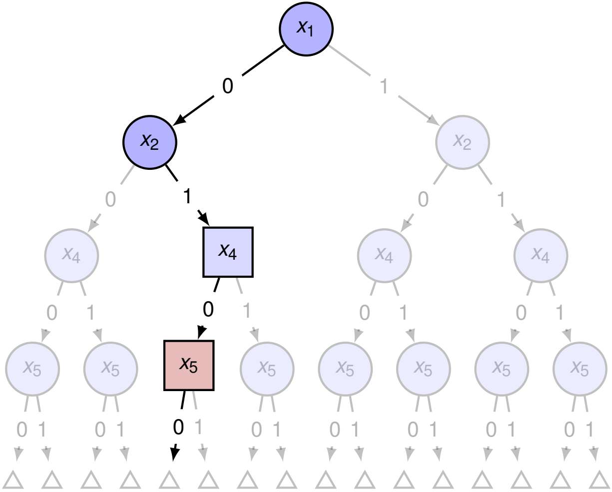
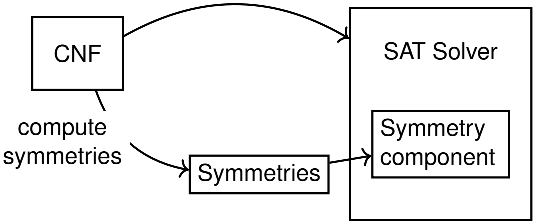


Use symmetries to deduce symmetrical facts.

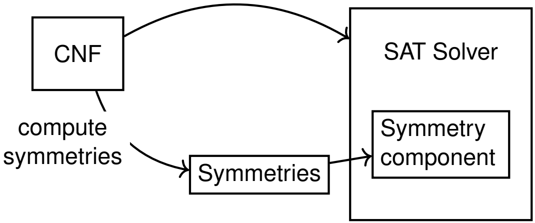
Dynamic Symmetry Breaking



State-of-the-art:

- Symmchaff [Sab05]
- Symmetry Propagation (SP) [DBdC+12]
- Symmetry Learning Scheme (SLS) [BNOS10]
- Symmetry Explanation Learning (SEL) [DBB17]

Dynamic Symmetry Breaking



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Observation:

Cannot handle some instances solved by static approach

Second contribution

Composing Symmetry Propagation and Effective Symmetry Breaking for SAT Solving

NFM'19 [MBK19]

ESBP + SP

Compose the symmetry propagation and the ESBP

prune the decision tree while accelerating its traversal

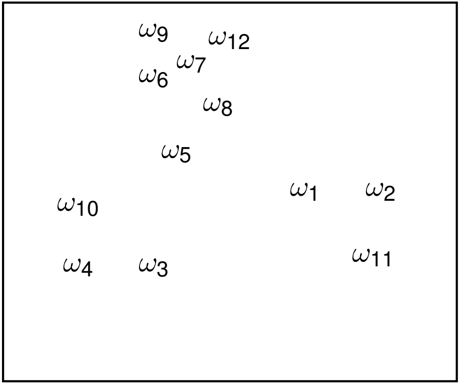
Problems:

- ESBP breaks symmetries (incrementally)
- SP considers the manipulated symmetries valid all time

In a hybrid approach, SP must be able to identify
valid symmetries

Local symmetry

- ◻ formula
- ω clause
- ω learnt clause

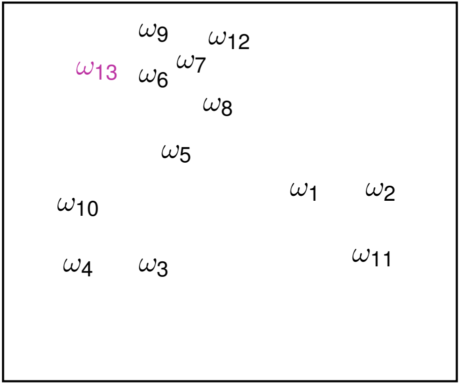


Local symmetries:

$\omega \leftarrow \{g_1, g_2, g_3\}$

Local symmetry

◻	formula
ω	clause
ω	learnt clause
ω	ESBP



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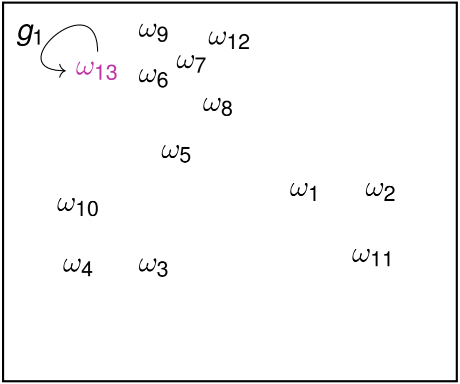

Local symmetries:

$\omega \leftarrow \{g_1, g_2, g_3\}$

$\omega \leftarrow \{g_1\}$

- Compute valid local symmetries
- On the fly
- At minimal cost

Local symmetry

□	formula
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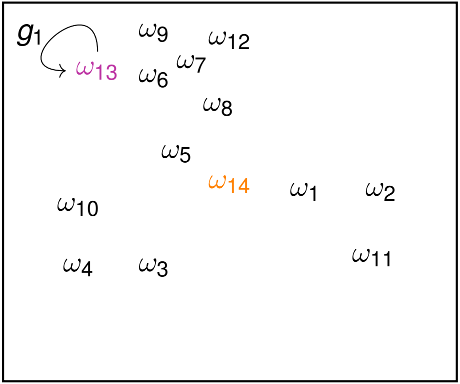

Local symmetries:

$\omega \leftarrow \{g_1, g_2, g_3\}$

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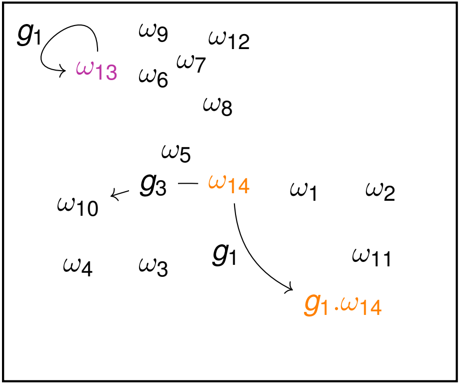
Inductive construction

Local symmetry

$\square$	formula
ω	clause
ω	learnt clause
ω	ESBP



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$\omega \leftarrow \{g_1, g_3\}$

- Compute valid local symmetries
- On the fly
- At minimal cost

Inductive construction

Experimental results

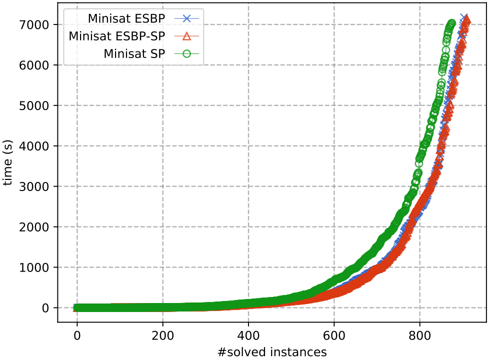
Benchmark:

- from SAT contests 2012 – 2018
- filter: `bliss` finds symmetries in 1000 seconds
- 1400 symmetric instances (out of 4000)

Setup:

- three tools
  - MiniSat SP (Minisat with Symmetry Propagation)
  - MiniSat ESBP (Minisat with CDCL[Sym])
  - **Minisat ESBP-SP** (our approach)
- 7200 seconds timeout

Experimental results



Solver	PAR-2	SAT	UNSAT
SP	1674h00	406	470
ESBP	1578h30	416	488
ESBP-SP	**1570h15**	**420**	**491**

Conclusion & Perspectives

Conclusion

- A new dynamic symmetry breaking approach
  - Generation of SBP on the fly
  - Package as a library cosy usable with any CDCL solver
- A new hybrid approach (ESBP-SP)
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- Exploitation of partial symmetries
- Symmetries and parallel SAT solver

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Thanks !

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CDCL in action TODO

$$
\begin{aligned}
\omega_1 &= \{x_1, x_2, x_3\} \\
\omega_2 &= \{x_4, x_5, x_6\} \\
\omega_3 &= \{\neg x_1, \neg x_5\} \\
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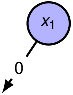

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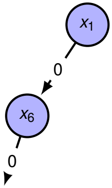

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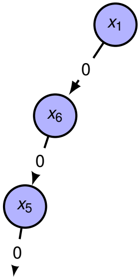

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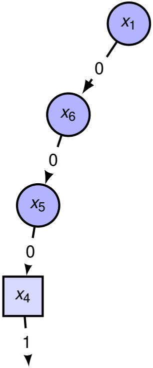

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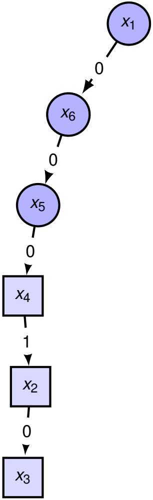

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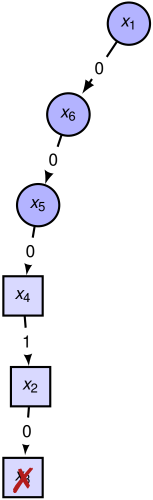

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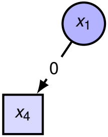

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$$\omega_7 = \{x_1, \neg x_4\}$$

Weakly active symmetries

Logical consequence

When ω is satisfied in all satisfying assignments of φ, we say that ω is a logical consequence of φ, and we denote this by $\varphi \vdash \omega$.

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Weakly active symmetries

Let a subset $\delta \subseteq \alpha$, a symmetry σ of φ such that $\varphi \cup \delta \vdash \varphi \cup \alpha \wedge \sigma.\delta \subseteq \alpha$ then σ is weakly active symmetry.

Weakly active symmetries

Logical consequence

When ω is satisfied in all satisfying assignments of φ, we say that ω is a logical consequence of φ, and we denote this by $\varphi \vdash \omega$.

Weakly active symmetries

Let a subset $\delta \subseteq \alpha$, a symmetry σ of φ such that $\varphi \cup \delta \vdash \varphi \cup \alpha \wedge \sigma.\delta \subseteq \alpha$ then σ is weakly active symmetry.

Symmetry propagation

Let σ a weakly active symmetry, then

$$\varphi \cup \alpha \vdash \{l\} \Leftrightarrow \varphi \cup \alpha \vdash \sigma.\{l\}$$

Local symmetries

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Local Symmetries

Let φ be a formula. We define $L_{\omega,\varphi}$, the set of *local symmetries* for a clause ω, and with respect to a formula φ, as follows:

$$L_{\omega,\varphi} = \{\sigma \in \mathfrak{S} \mid \varphi \vdash \sigma.\omega\}$$

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We can state that:

$$\bigcap_{\omega \in \varphi} L_{\omega,\varphi} \subseteq G.$$

Computing local symmetries

Formula can be decomposed as : $\varphi = \varphi_o \cup \varphi_e \cup \varphi_d$ where

- φ_o is the set of the original clauses
- φ_e is the set of ESBPs
- φ_d is the set of deduced clauses.

Local symmetries

- $\omega \in \varphi_o, L_{\omega,\varphi} \supseteq G$
- $\omega \in \varphi_e, L_{\omega,\varphi} \supseteq Stab(\omega) = \{\sigma \in G \mid \omega = \sigma.\omega\}$
- $\omega \in \varphi_d, L_{\omega,\varphi} \supseteq (\bigcap_{\omega' \in \varphi_1} L_{\omega',\varphi}) \cup Stab(\omega)$

  where φ_1 is the set of clauses that derives ω.

Generates symmetry breaking predicates (SBP)

- Define lexicographic order
  - Define total order on variables
  - Define minimal value
- Forbid non minimal assignment for each orbit

Example:

$$x_1 \leq x_2 \leq x_3 \leq x_4 \leq x_5 \leq x_6 \leq x_7 \leq x_8; \mathtt{F} < \mathtt{T}$$

$$g = (x_1 \;\; x_2)(x_4 \;\; x_5)(x_7 \;\; x_8)$$

	x_1	x_2	x_3	x_4	x_5	$\cdots$	lex-leader	SBP

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O_2	F	F	–	F	T	$\cdots$	✓	
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				$\cdots$				

Example

$$g_1 = (x_2 \;\; x_3)(x_5 \;\; x_6)(x_8 \;\; x_9) \qquad\qquad g_2 = (x_1 \;\; x_2)(x_4 \;\; x_5)(x_7 \;\; x_8)$$

$$\mathtt{F} < \mathtt{T} \qquad x_1 \le x_2 \le x_3 \le x_4 \le x_5 \le x_6 \le x_7 \le x_8 \le x_9$$

$\overline{g_1}$

$$\alpha = \underline{\mathrm{U}} \quad \overline{\mathrm{U}} \quad \mathrm{U} \quad \mathrm{U} \quad \mathrm{U} \quad \mathrm{U} \quad \mathrm{U} \quad \mathrm{U} \quad \mathrm{U}$$

$\underline{g_2}$

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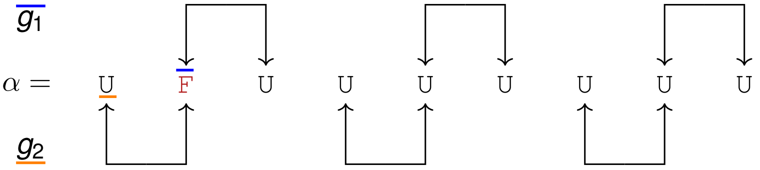

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$$\underline{g_2}$$

g_2 generates ESBP $\omega = \{\neg x_1, x_2\}$

Example

1. `reducer`: $\alpha(g.x) \leq \alpha(x)$
2. `inactive`: $\alpha(x) \leq \alpha(g.x)$
3. `active`: $\alpha(g.x)$ or $\alpha(x)$ is unassigned

$$x_1 \leq x_2 \leq x_3 \leq x_4 \leq x_5 \leq x_6 \leq x_7 \leq x_8 \; ; \; \mathtt{F} < \mathtt{T}$$

$$g_1 = \begin{array}{cccccc} (x_2 & x_3) & (x_5 & x_6) & (x_8 & x_9) \\ \uparrow & & & & & \end{array} \Bigg| \begin{array}{cc} x = x_2 & g.x = x_3 \\ & \mathtt{active} \end{array}$$

$$g_2 = \begin{array}{cccccc} (x_1 & x_2) & (x_4 & x_5) & (x_7 & x_8) \\ \uparrow & & & & & \end{array} \Bigg| \begin{array}{cc} x = x_1 & g.x = x_2 \\ & \mathtt{active} \end{array}$$

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$$\alpha = \{ \qquad \qquad \}$$

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$$\ldots$$

$$\alpha = \{\neg x_2 \qquad\qquad \}$$

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$$g_2 = \quad (\underset{\uparrow}{x_1} \quad x_2) \quad (x_4 \quad x_5) \quad (x_7 \quad x_8) \;\Big|\; x = x_1 \quad \begin{array}{l} g.x = x_2 \\ \texttt{reducer} \end{array}$$

$$\ldots$$

$$\alpha = \{\neg x_2, \neg x_3, x_1\}$$

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$$\ldots$$

$$\alpha = \{\neg x_2, \neg x_3, x_1\}$$

g_2 generates $\omega = \{\neg x_1, x_2\}$

Encoding the problem

$$
\begin{array}{ll}
(A,1)(A,2)(A,3) & x_1 \vee x_2 \vee x_3 \\
(B,1)(B,2)(B,3) & x_4 \vee x_5 \vee x_6 \\
(C,1)(C,2)(C,3) & x_7 \vee x_8 \vee x_9 \\
\\
\neg(A,1)\neg(B,1) & \neg x_1 \vee \neg x_4 \\
\neg(A,1)\neg(C,1) & \neg x_1 \vee \neg x_7 \\
\neg(B,1)\neg(C,1) & \neg x_4 \vee \neg x_7 \\
\\
\neg(A,2)\neg(B,2) & \neg x_2 \vee \neg x_5 \\
\neg(A,2)\neg(C,2) & \neg x_2 \vee \neg x_8 \\
\neg(B,2)\neg(C,2) & \neg x_5 \vee \neg x_8 \\
\\
\neg(A,3)\neg(B,3) & \neg x_3 \vee \neg x_6 \\
\neg(A,3)\neg(C,3) & \neg x_3 \vee \neg x_9 \\
\neg(B,3)\neg(C,3) & \neg x_6 \vee \neg x_9
\end{array}
$$