Exploitation of dynamic symmetries for solving SAT problems

Thèse de doctorat de Sorbonne Université

Hakan METIN

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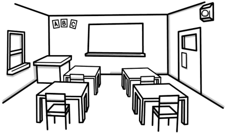
Motivation

Boolean SATisfiability is widely used in different domains

- Artificial intelligence (planning [KS$^+$92], ...)
- Bioinformatics (haplotype inference [LMS06], ...)
- Security (cryptanalysis [MM00], ...)
- Computationally hard problems (ramsey numbers, graph coloring, ...)
- Formal methods,(bounded model checking [BCCZ99], ...)

SAT an example



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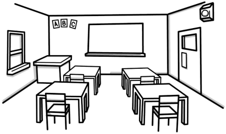

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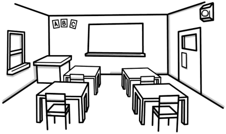

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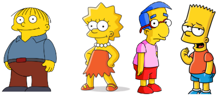

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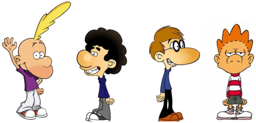
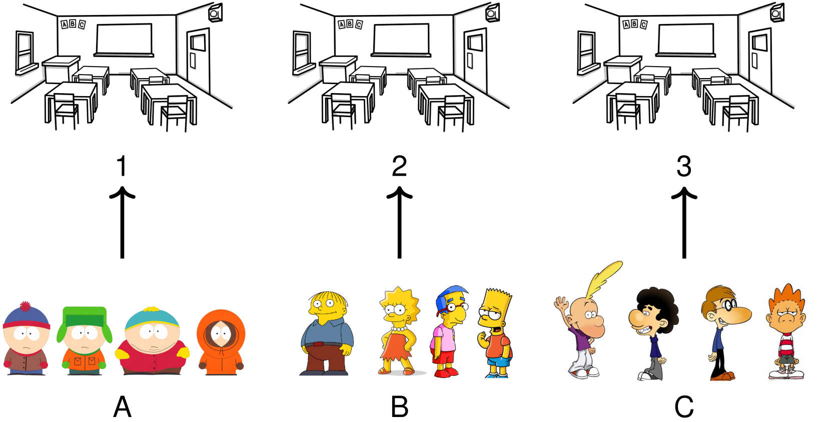


C

Is it possible to attribute each group to a classroom?

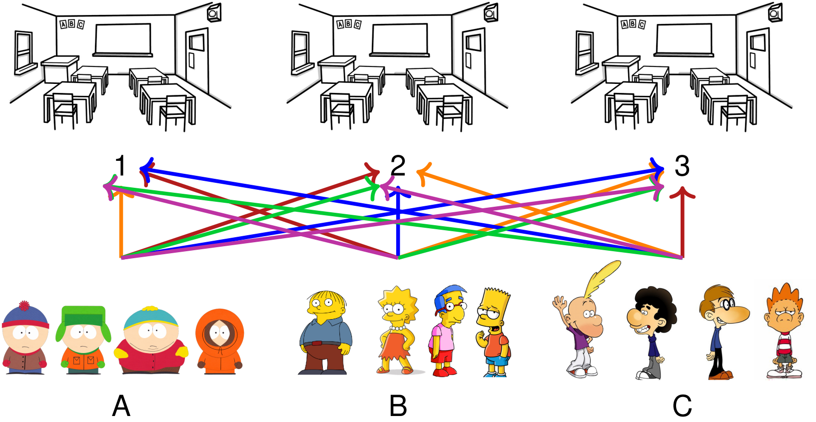
SAT an example



Is it possible to attribute each group to a classroom?

YES!

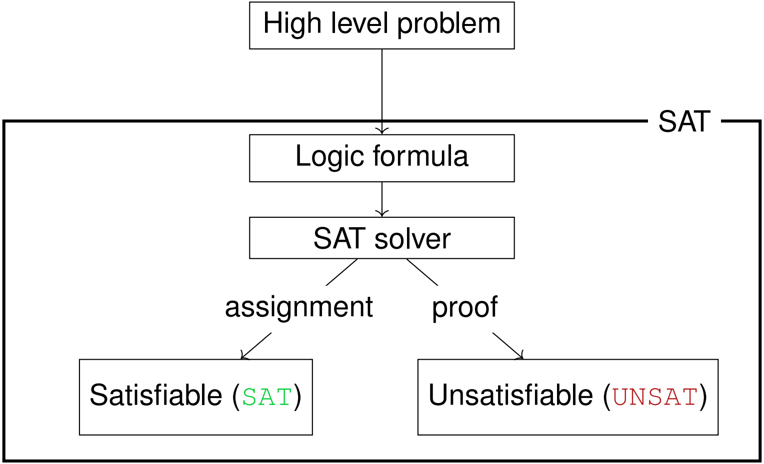
SAT an example



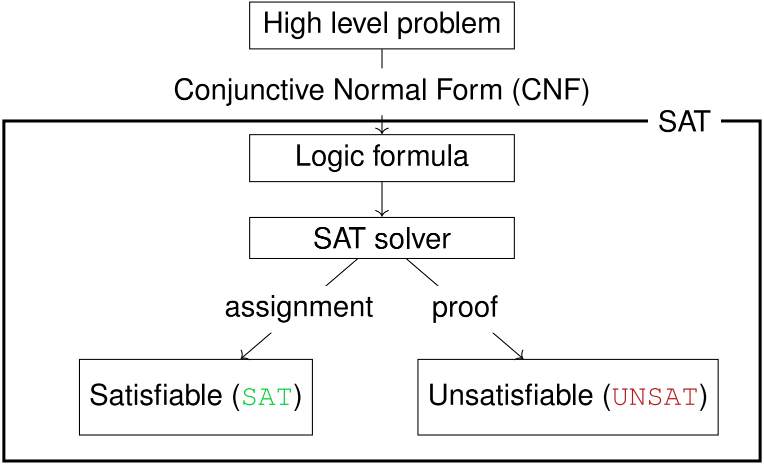
Is it possible to attribute each group to a classroom?

YES! Many solutions

Boolean SATisfiability problem



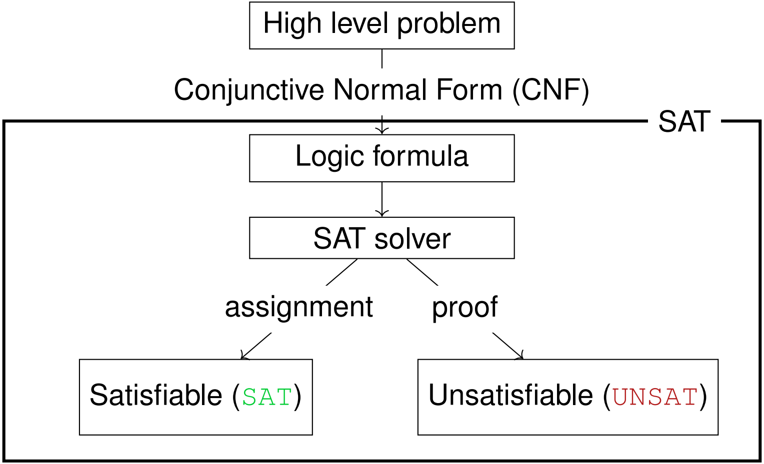
Boolean SATisfiability problem



CNF representation:

$$\underbrace{(x_1 \lor x_2 \lor \neg x_3)}_{\text{Clause with literals } x_1, x_2, \neg x_3}$$

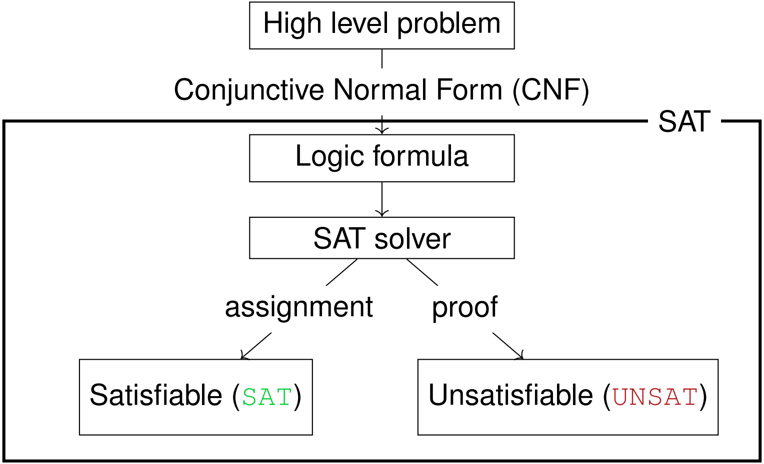
Boolean SATisfiability problem



CNF representation:

$$\overbrace{\underbrace{(x_1 \lor x_2 \lor \neg x_3)}_{\textit{Clause}} \land (\neg x_1 \lor \neg x_2) \land (x_2 \lor \neg x_4)}^{\text{Formula (CNF)}}$$

Boolean SATisfiability problem



Clause representation as a set:

$$(x_1 \vee x_2 \vee \neg x_3) \to \{x_1, x_2, \neg x_3\}$$

SAT Solving

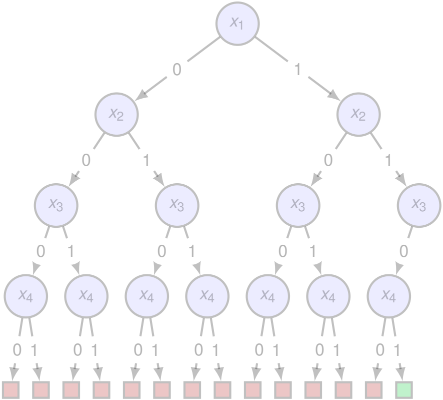
Solving SAT formula is known to be **NP-complete** [Coo71]

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 action



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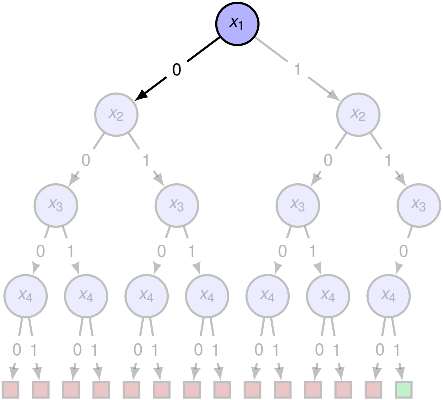

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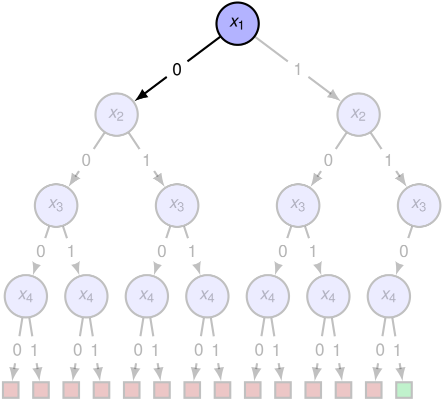

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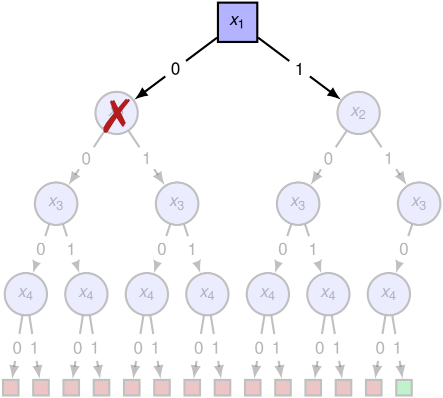

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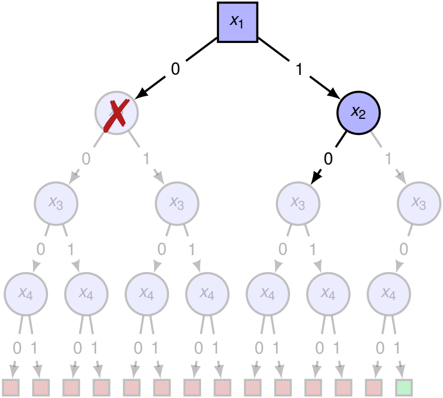

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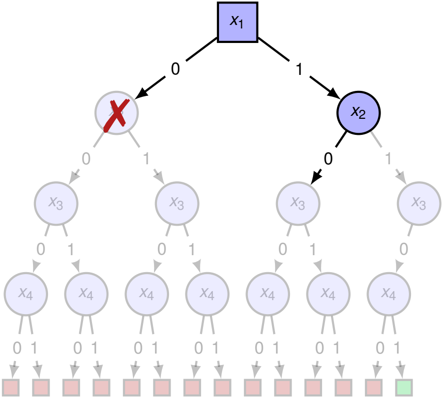

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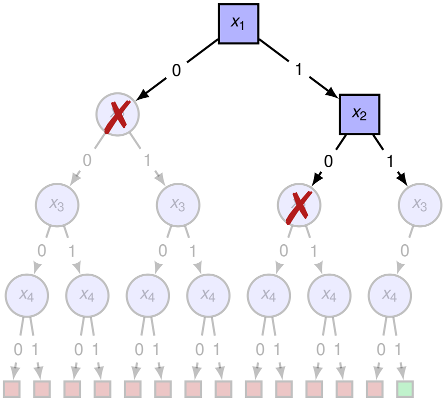

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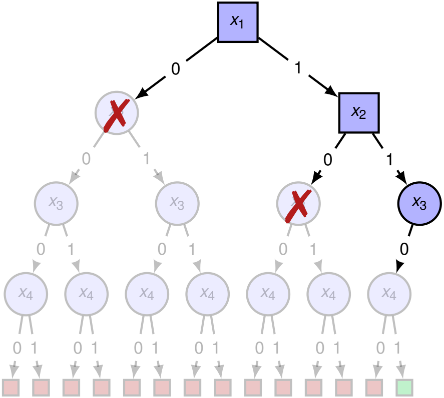

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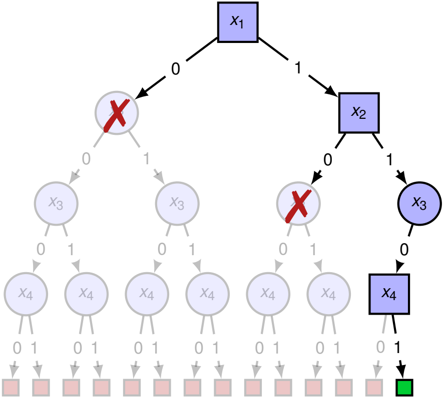

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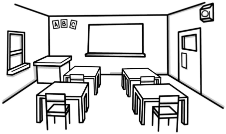
An UNSAT example



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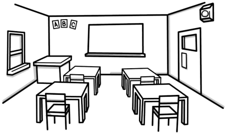

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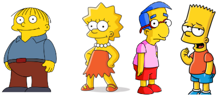

B

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Is it possible to attribute each group to a classroom?

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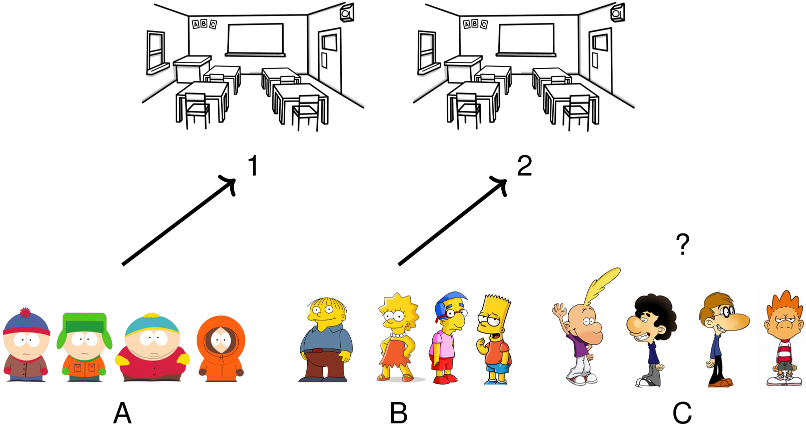

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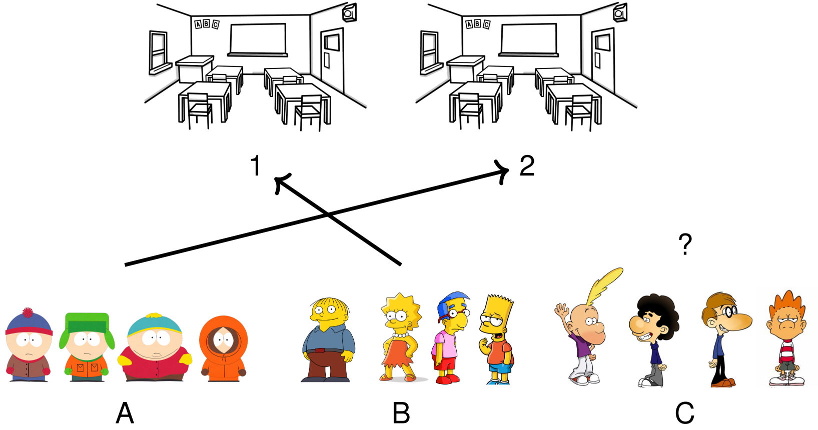

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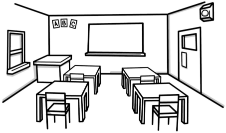

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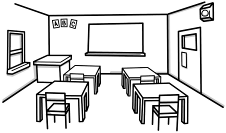

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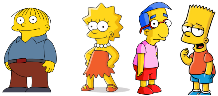
. . .

A



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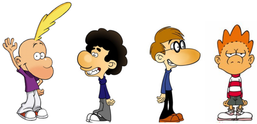

C

Is it possible to attribute each group to a classroom?

No!

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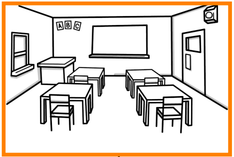

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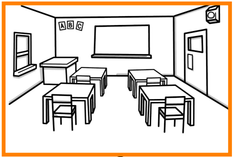

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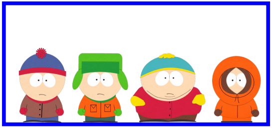

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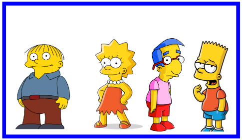

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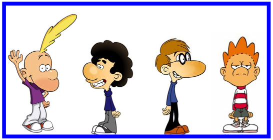

C

Is it possible to attribute each group to a classroom?

No!

Presence of symmetries hinders the performance of the solver

Symmetry

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

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

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

The set of symmetries of a formula is a group noted G

Computing symmetries of a SAT problem

CNF formula

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

Computing symmetries of a SAT problem

CNF formula

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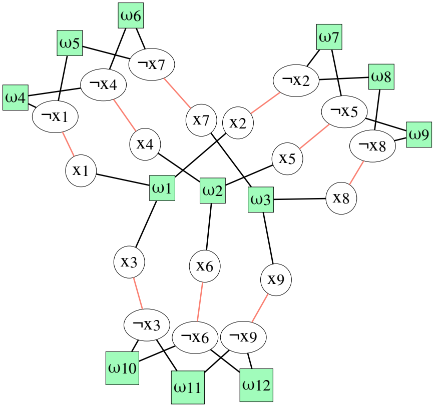
$$\wedge(\neg x_2 \vee \neg x_5) \wedge (\neg x_2 \vee \neg x_8) \wedge (\neg x_5 \vee \neg x_8)$$
$$\wedge(\neg x_3 \vee \neg x_6) \wedge (\neg x_3 \vee \neg x_9) \wedge (\neg x_6 \vee \neg x_9)$$

$\Downarrow$ $\Downarrow$

colored graph



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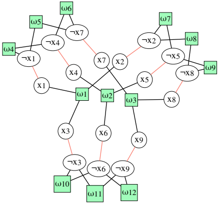

$\|$ $\|$

graph automorphism

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

Computing symmetries of a SAT problem

CNF formula

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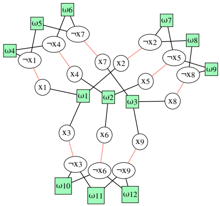

$\|$ $\|$

graph automorphism

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

$\Downarrow$ $\Downarrow$

set of symmetries

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

Orbit

Orbit of an assignment $\alpha = G.\alpha = \{g.\alpha \mid g \in G\}$

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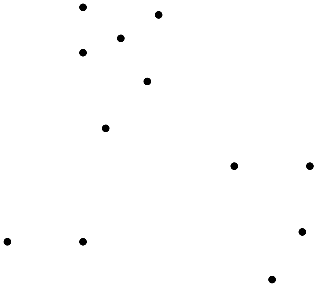
Example:

- full assignment



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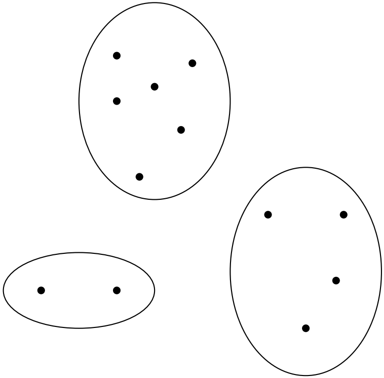
Example:

- full assignment
- orbit



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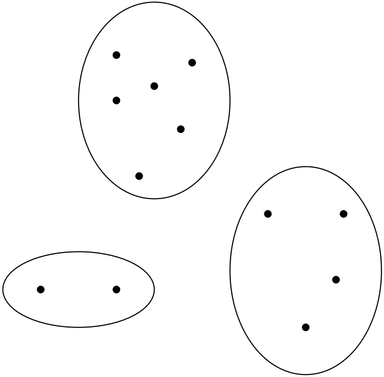
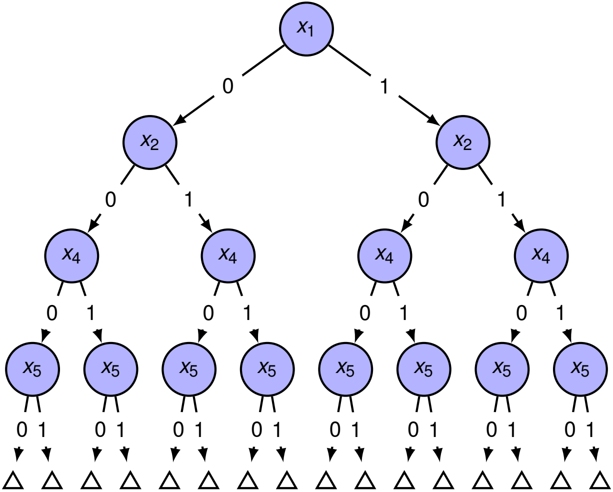


Equivalence relation with respect to SAT:

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

Using symmetries to prune the search space

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



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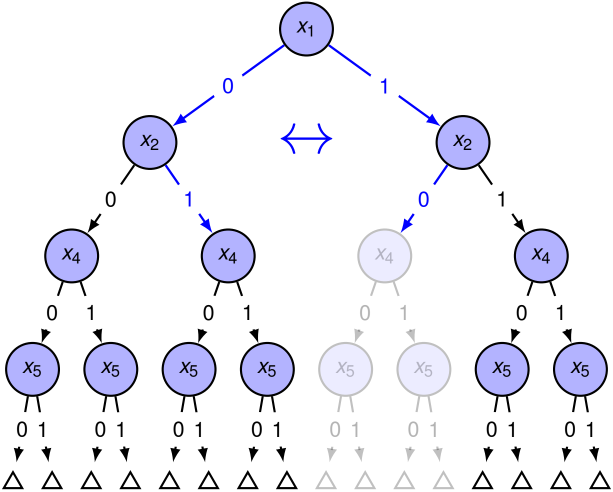

Generates symmetry breaking predicates (SBP)

- 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_1	F	T	–	–	–	$\cdots$	✓	

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O_1	F	T	–	–	–	$\cdots$	✓	
	T	F	–	–	–	$\cdots$	✗	$\rightarrow \neg x_1 \vee x_2$

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O_1	F	T	–	–	–	$\cdots$	✓	
	T	F	–	–	–	$\cdots$	✗	$\rightarrow \neg x_1 \vee x_2$
O_2	F	F	–	F	T	$\cdots$	✓	

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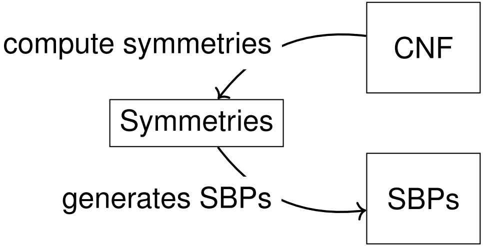
	F	F	–	T	F	$\cdots$	✗	$\rightarrow x_1 \vee x_2 \vee \neg x_4 \vee x_5$
				$\cdots$				

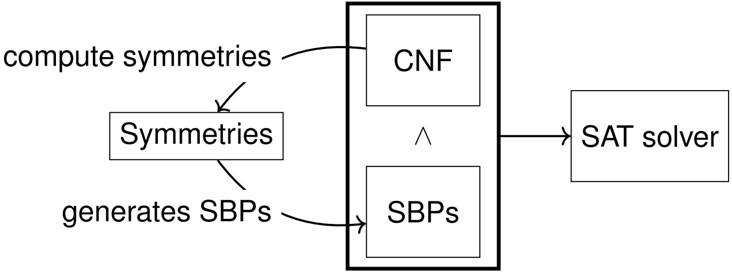
Static symmetry breaking



Different approaches:

- Shatter [ASM06]
- BreakID [DBBD16]
- ...

Static symmetry breaking



Different approaches:

- Shatter [ASM06]
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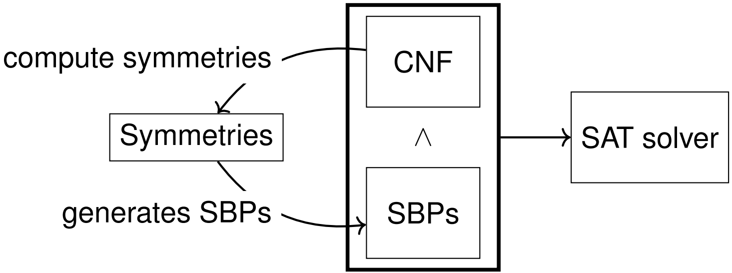
Static symmetry breaking



Different approaches:

- Shatter [ASM06]
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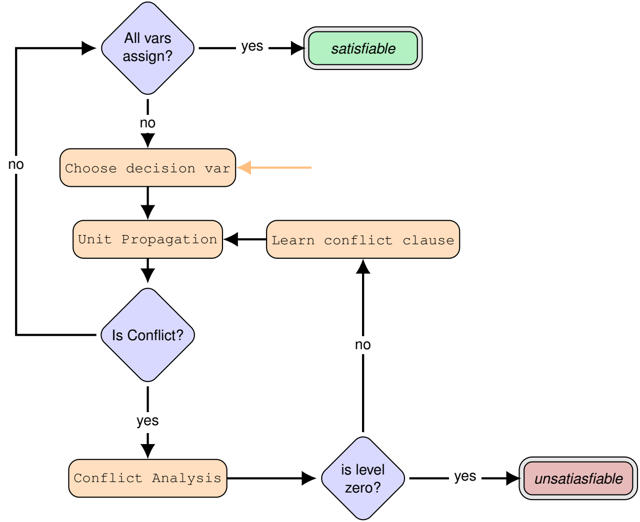
- ...

The solver can ”explode” instead of being helped

Our contribution CDCL[Sym] [MBCK18]

Compute and inject SBP opportunistically, during the solving



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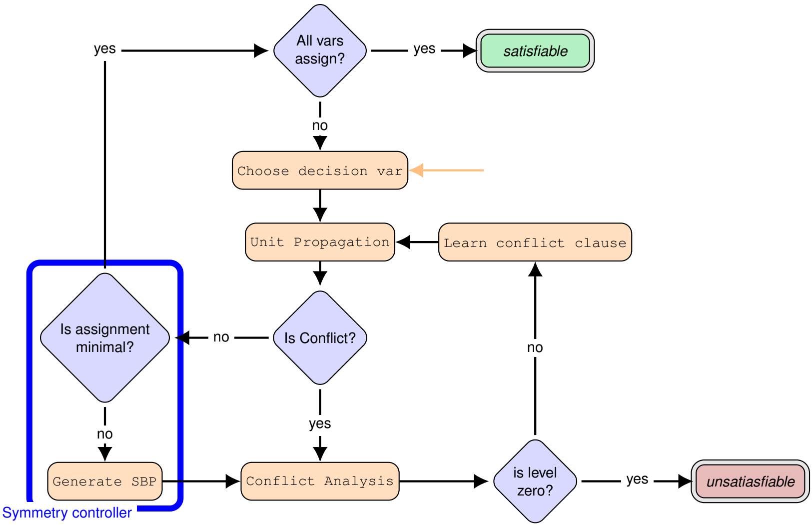

Symmetry status

- `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`

Update whenever variables are assigned / unassigned

Example

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

$$\alpha = \quad x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5 \quad x_6 \quad x_7 \quad x_8 \quad x_9$$

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

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

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

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

$$\dots$$

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

Example

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

$$\ldots$$

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

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$$\begin{array}{llllllll|ll} g_2 = & (x_1 & x_2) & (x_4 & x_5) & (x_7 & x_8) & & x = x_1 & g.x = x_2 \\ & \uparrow & & & & & & & & \mathtt{reducer} \end{array}$$

$$\dots$$

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

Example

1. `reducer`: $\alpha(g.x) \leq \alpha(x)$
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g_2 generates $\omega = \{\neg x_1, x_2\}$

CDCL[Sym] Implementation

- Packaged as a library **cosy**[1]
- Lightweight
- Fast Update and low memory
- Follows symmetry status

- Works with any enumerative SAT solver

[1] `https://github.com/lip6/cosy`

Experiments

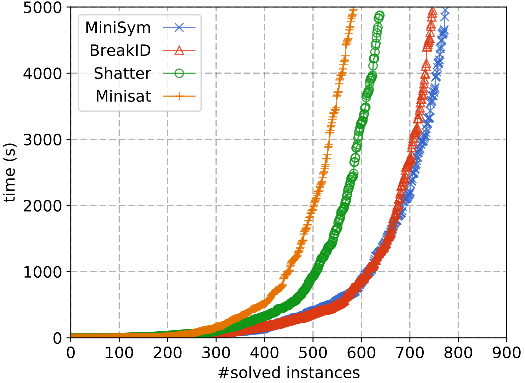
Benchmark:

- from SAT contests 2012 – 2017
- filter: `bliss` finds significant symmetries in 1000s
- 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)
- 5000s timeout, 8GB memory
- includes time to compute symmetries (except for MiniSat)

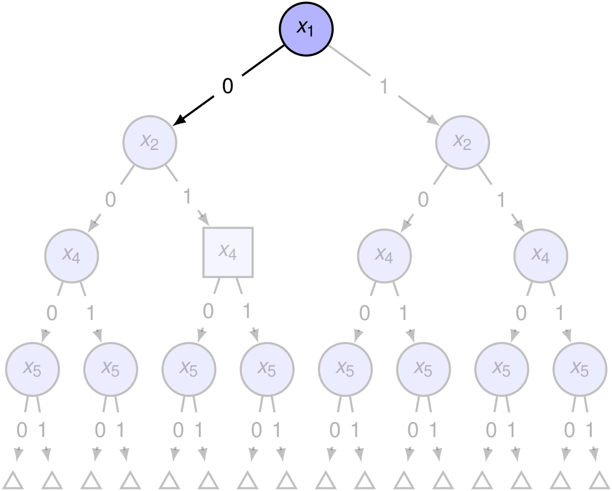
Experimental results



Solver	PAR-2	ALL	SAT	UNSAT
MiniSAT	2243h	586	325	261
Shatter	2088h	640	316	324
BreakID	1790h	749	334	415
MiniSym	**1735h**	**775**	**336**	**439**

Using symmetries to accelerate the tree traversal

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



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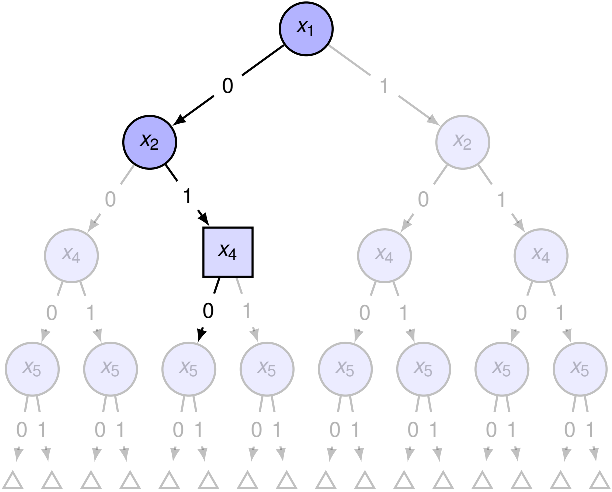

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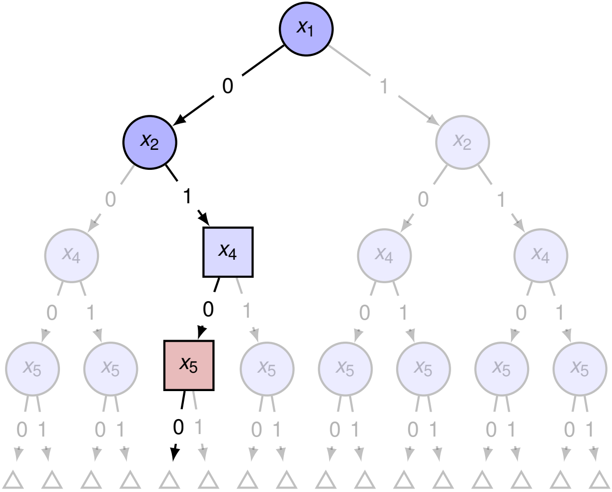
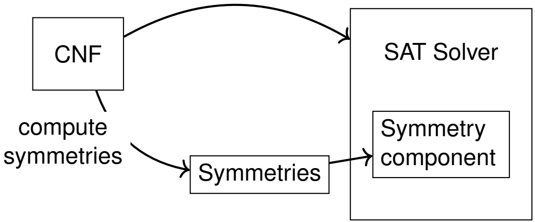


Use symmetries to deduce symmetrical facts.

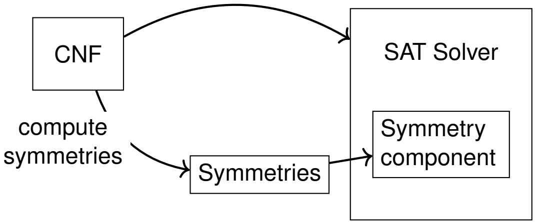
Dynamic Symmetry Breaking



Different approaches:

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

Dynamic Symmetry Breaking



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- ...

Cannot handle some instances solved by static approach

ESBP + SP [MBK19]

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 symmetries

$$\text{Formula} \leftarrow \text{(Symmetries)} \qquad \begin{aligned} \omega_1 &\leftarrow \text{(Local symmetries)} \\ \omega_2 &\leftarrow \text{(Local symmetries)} \\ \omega_3 &\leftarrow \text{(Local symmetries)} \\ \omega_4 &\leftarrow \text{(Local symmetries)} \end{aligned}$$

Macro level $\rightarrow$ Micro level

Local symmetries

$$\omega_1 \leftarrow \text{(Local symmetries)}$$
$$\omega_2 \leftarrow \text{(Local symmetries)}$$
$$\text{Formula} \leftarrow \text{(Symmetries)} \qquad \omega_3 \leftarrow \text{(Local symmetries)}$$
$$\omega_4 \leftarrow \text{(Local symmetries)}$$
$$\omega_5$$

Macro level $\rightarrow$ Micro level

Local symmetries

$$\text{Formula} \leftarrow (\text{Symmetries}) \qquad \begin{aligned} \omega_1 &\leftarrow (\text{Local symmetries}) \\ \omega_2 &\leftarrow (\text{Local symmetries}) \\ \omega_3 &\leftarrow (\text{Local symmetries}) \\ \omega_4 &\leftarrow (\text{Local symmetries}) \\ \omega_5 &\leftarrow (\text{Local symmetries}) \end{aligned}$$

Macro level $\rightarrow$ Micro level

Compute valid local symmetries on-the-fly at a minimal cost.

Local symmetries

$\omega_1 \leftarrow$ (Local symmetries)

$\omega_2 \leftarrow$ (Local symmetries)

Formula $\leftarrow$ (Symmetries)

$\omega_3 \leftarrow$ (Local symmetries)

$\omega_4 \leftarrow$ (Local symmetries)

ω_5

Macro level $\rightarrow$ Micro level

Compute valid local symmetries on-the-fly at a minimal cost.

- Inductive construction of the valid symmetries
- During the solving
- At a minimal cost

Experimental results

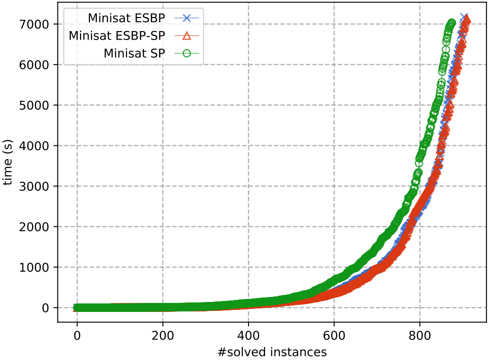
Benchmark:

- from SAT contests 2012 – 2018
- retain only instances for which `bliss` finds significant symmetries in 1000s
- 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)
- 7200s timeout

Experimental results



Solver	PAR-2	ALL	SAT	UNSAT
SP	1674h00	876	406	470
ESBP	1578h30	904	416	488
ESBP-SP	**1570h15**	**911**	**420**	**491**

Conclusion

- A new dynamic symmetry breaking approach
  - Generation of SBP on the fly
  - Package as a library cosy usable with any CDCL solver
  - Overcomes drawbacks of the existing approaches

- A new hybrid approach (ESBP-SP)
  - Take advantage of static and dynamic approach
  - Introduce local symmetries

Perspectives

- Combination of CDCL[Sym] with other dynamic symmetry breaking approach

- Exploitation of partial symmetries

Perspectives

- Combination of CDCL[Sym] with other dynamic symmetry breaking approach

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Thanks !

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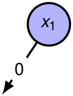
CDCL in action TODO

$$
\begin{aligned}
\omega_1 &= \{x_1, x_2, x_3\} \\
\omega_2 &= \{x_4, x_5, x_6\} \\
\omega_3 &= \{\neg x_1, \neg x_5\} \\
\omega_4 &= \{\neg x_2, \neg x_4\} \\
\omega_5 &= \{\neg x_3, \neg x_4\} \\
\omega_6 &= \{\neg x_3, \neg x_6\}
\end{aligned}
$$

CDCL in action TODO



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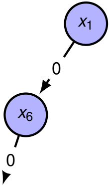

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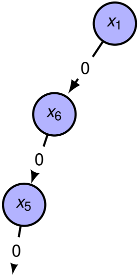

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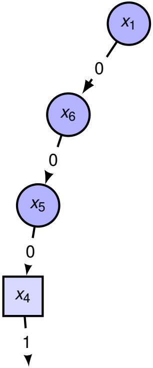
CDCL in action TODO



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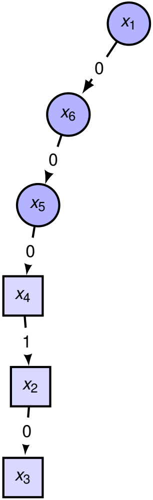
CDCL in action TODO



$$\omega_1 = \{x_1, x_2, x_3\}$$
$$\omega_2 = \{x_4, x_5, x_6\}$$
$$\omega_3 = \{\neg x_1, \neg x_5\}$$
$$\omega_4 = \{\neg x_2, \neg x_4\}$$
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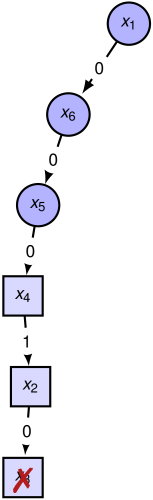
CDCL in action TODO



$$
\begin{aligned}
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$$

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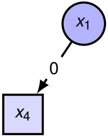

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$$\omega_7 = \{x_1, \neg x_4\}$$

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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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.