

Conflict-Driven Clause Learning

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The Satisfiability (SAT) problem

$$\begin{aligned} & (x_5 \vee x_8 \vee \bar{x}_2) \wedge (x_2 \vee \bar{x}_1 \vee \bar{x}_3) \wedge (\bar{x}_8 \vee \bar{x}_3 \vee \bar{x}_7) \wedge (\bar{x}_5 \vee x_3 \vee x_8) \wedge \\ & (\bar{x}_6 \vee \bar{x}_1 \vee \bar{x}_5) \wedge (x_8 \vee \bar{x}_9 \vee x_3) \wedge (x_2 \vee x_1 \vee x_3) \wedge (\bar{x}_1 \vee x_8 \vee x_4) \wedge \\ & (\bar{x}_9 \vee \bar{x}_6 \vee x_8) \wedge (x_8 \vee x_3 \vee \bar{x}_9) \wedge (x_9 \vee \bar{x}_3 \vee x_8) \wedge (x_6 \vee \bar{x}_9 \vee x_5) \wedge \\ & (x_2 \vee \bar{x}_3 \vee \bar{x}_8) \wedge (x_8 \vee \bar{x}_6 \vee \bar{x}_3) \wedge (x_8 \vee \bar{x}_3 \vee \bar{x}_1) \wedge (\bar{x}_8 \vee x_6 \vee \bar{x}_2) \wedge \\ & (x_7 \vee x_9 \vee \bar{x}_2) \wedge (x_8 \vee \bar{x}_9 \vee x_2) \wedge (\bar{x}_1 \vee \bar{x}_9 \vee x_4) \wedge (x_8 \vee x_1 \vee \bar{x}_2) \wedge \\ & (x_3 \vee \bar{x}_4 \vee \bar{x}_6) \wedge (\bar{x}_1 \vee \bar{x}_7 \vee x_5) \wedge (\bar{x}_7 \vee x_1 \vee x_6) \wedge (\bar{x}_5 \vee x_4 \vee \bar{x}_6) \wedge \\ & (\bar{x}_4 \vee x_9 \vee \bar{x}_8) \wedge (x_2 \vee x_9 \vee x_1) \wedge (x_5 \vee \bar{x}_7 \vee x_1) \wedge (\bar{x}_7 \vee \bar{x}_9 \vee \bar{x}_6) \wedge \\ & (x_2 \vee x_5 \vee x_4) \wedge (x_8 \vee \bar{x}_4 \vee x_5) \wedge (x_5 \vee x_9 \vee x_3) \wedge (\bar{x}_5 \vee \bar{x}_7 \vee x_9) \wedge \\ & (x_2 \vee \bar{x}_8 \vee x_1) \wedge (\bar{x}_7 \vee x_1 \vee x_5) \wedge (x_1 \vee x_4 \vee x_3) \wedge (x_1 \vee \bar{x}_9 \vee \bar{x}_4) \wedge \\ & (x_3 \vee x_5 \vee x_6) \wedge (\bar{x}_6 \vee x_3 \vee \bar{x}_9) \wedge (\bar{x}_7 \vee x_5 \vee x_9) \wedge (x_7 \vee \bar{x}_5 \vee \bar{x}_2) \wedge \\ & (x_4 \vee x_7 \vee x_3) \wedge (x_4 \vee \bar{x}_9 \vee \bar{x}_7) \wedge (x_5 \vee \bar{x}_1 \vee x_7) \wedge (x_5 \vee \bar{x}_1 \vee x_7) \wedge \\ & (x_6 \vee x_7 \vee \bar{x}_3) \wedge (\bar{x}_8 \vee \bar{x}_6 \vee \bar{x}_7) \wedge (x_6 \vee x_2 \vee x_3) \wedge (\bar{x}_8 \vee x_2 \vee x_5) \end{aligned}$$

Does there exist an assignment satisfying all clauses?

Search for a satisfying assignment (or proof none exists)

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Conflict-driven Clause Learning: Overview

- ▶ Most successful architecture

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- ▶ Most successful architecture
- ▶ Superior on industrial benchmarks
- ▶ Brute-force?
 - ▶ Addition conflict clauses
 - ▶ Fast unit propagation
- ▶ Complete local search (for a refutation)?
- ▶ State-of-the-art (sequential) CDCL solvers:
CaDiCaL, Glucose, CryptoMiniSAT

Clause Learning

Data-structures

Heuristics

Clause Management

Conflict-Clause Minimization

Recent Advances and Conclusions

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Recent Advances and Conclusions

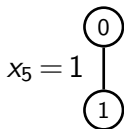
Conflict-driven SAT solvers: Search and Analysis

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0

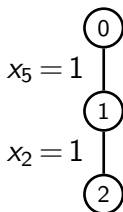
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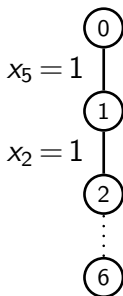
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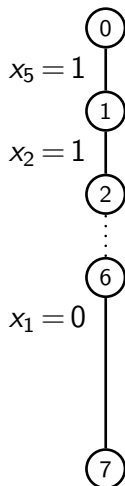
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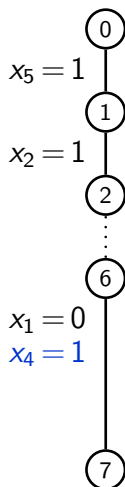
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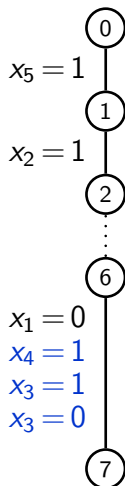
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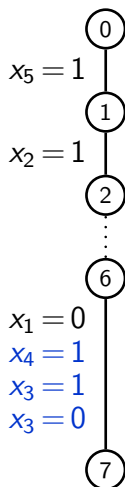
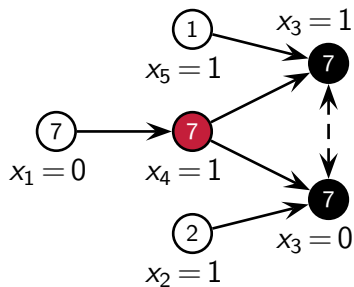
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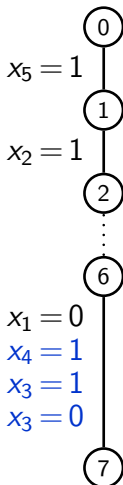
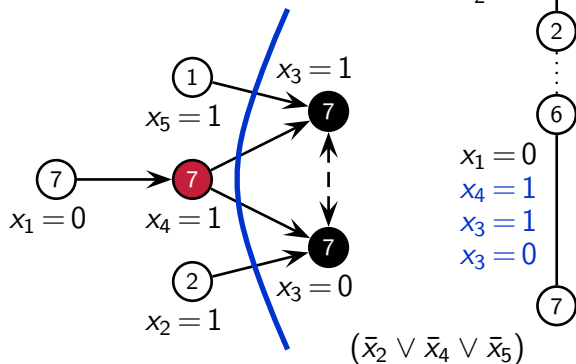
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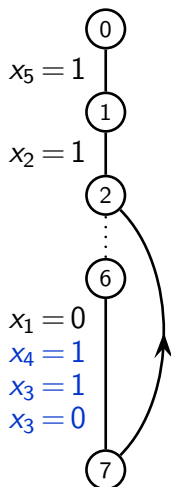
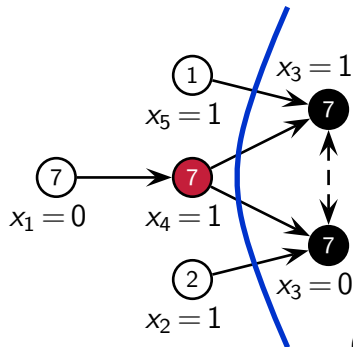
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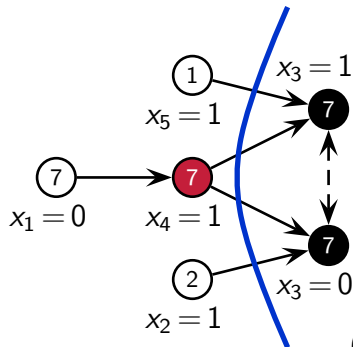
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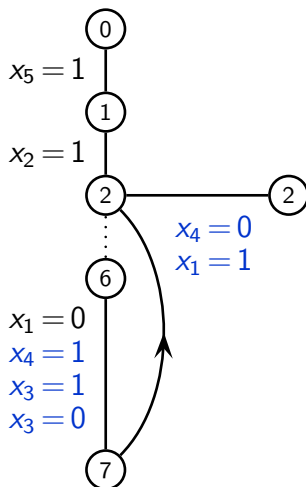
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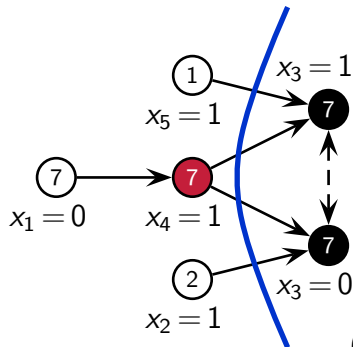


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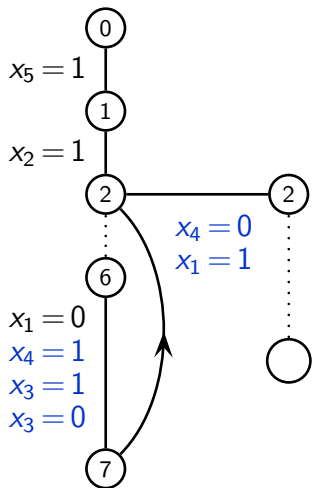


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$$(\bar{x}_2 \vee \bar{x}_4 \vee \bar{x}_5)$$



Implication graph [Marques-SilvaSakallah '96]

CDCL in a nutshell:

1. Main loop combines **efficient** problem simplification with **cheap**, but effective decision heuristics; (> 90% of time)
2. Reasoning kicks in if the current state is **conflicting**;
3. The current state is analyzed and turned into a **constraint**;
4. The constraint is **added** to the problem, the heuristics are **updated**, and the algorithm (partially) **restarts**.

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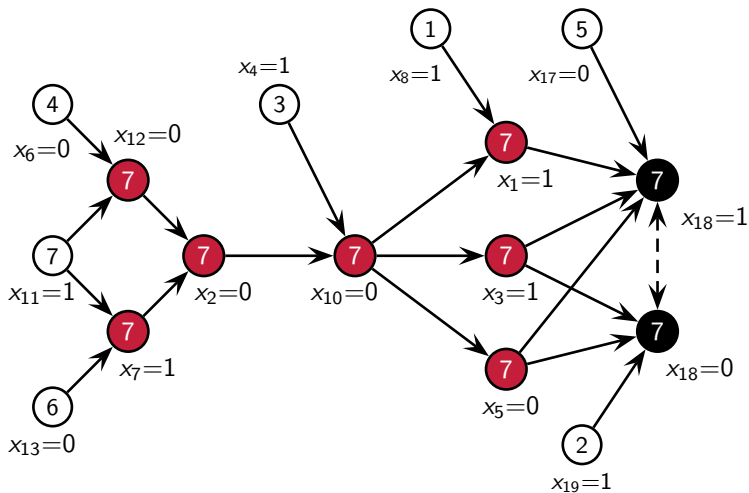
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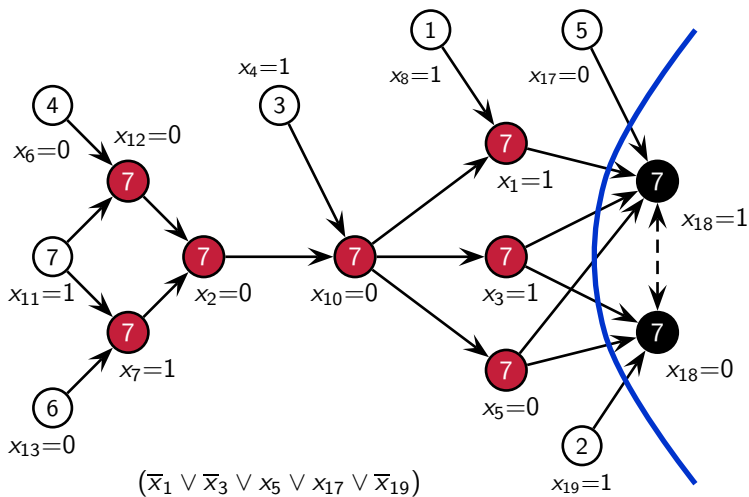
However, it has three weaknesses:

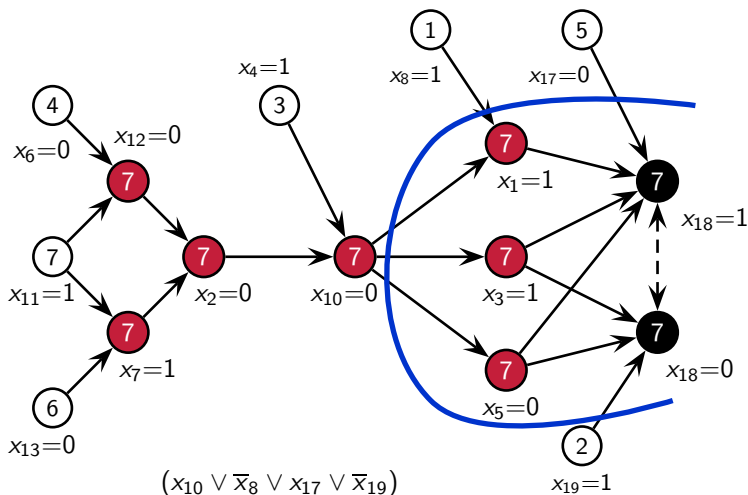
- ▶ CDCL is notoriously hard to **parallelize**;
- ▶ the **representation** impacts CDCL performance; and
- ▶ CDCL has **exponential runtime** on some “simple” problems.

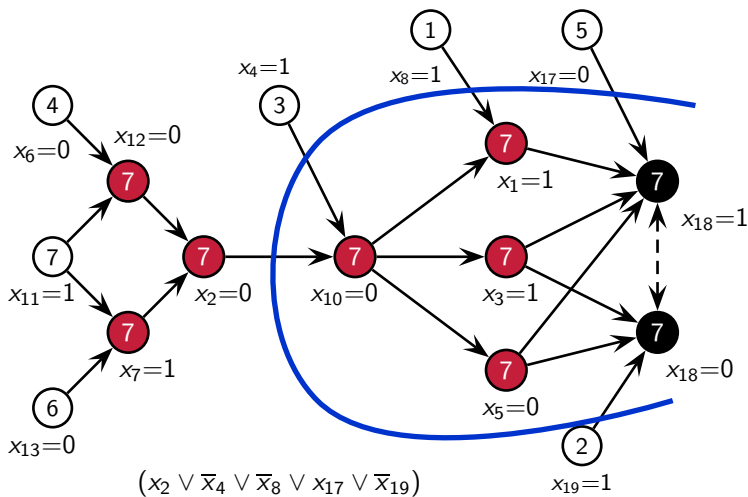
Conflict-driven Clause Learning: Pseudo-code

```
1: while TRUE do
2:    $l_{\text{decision}} := \text{Decide} ()$ 
3:   If no  $l_{\text{decision}}$  then return satisfiable
4:    $\mathcal{F} := \text{Simplify} (\mathcal{F}(l_{\text{decision}} \leftarrow 1))$ 
5:   while  $\mathcal{F}$  contains  $C_{\text{falsified}}$  do
6:      $C_{\text{conflict}} := \text{Analyze} (C_{\text{falsified}})$ 
7:     If  $C_{\text{conflict}} = \emptyset$  then return unsatisfiable
8:      $\text{BackTrack} (C_{\text{conflict}})$ 
9:      $\mathcal{F} := \text{Simplify} (\mathcal{F} \cup \{C_{\text{conflict}}\})$ 
10:  end while
11: end while
```



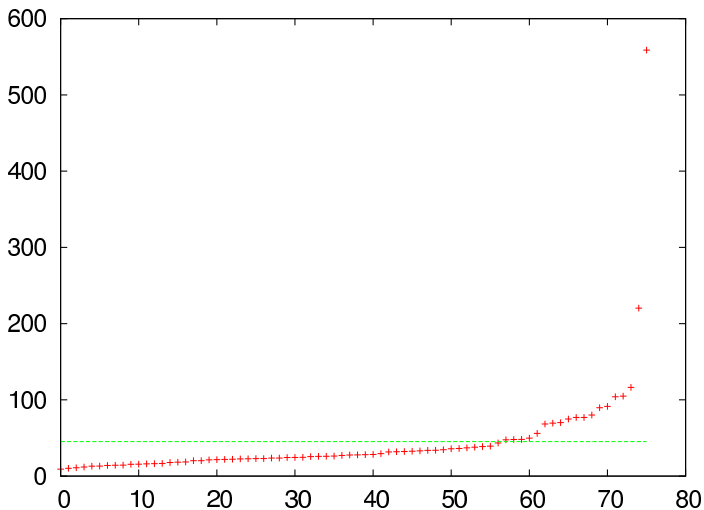






second unique implication point

Average Learned Clause Length



Clause Learning

Data-structures

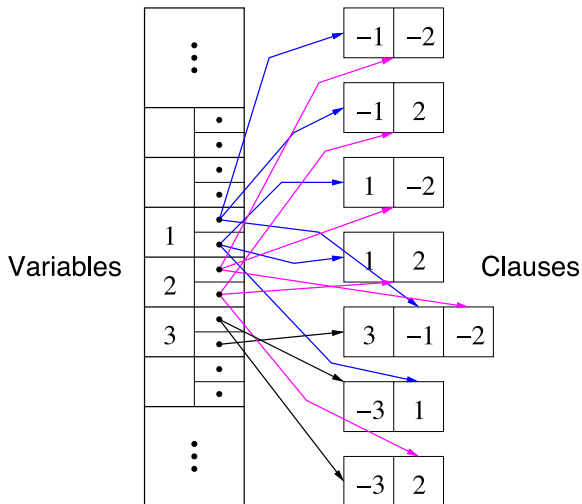
Heuristics

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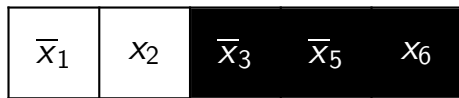
Recent Advances and Conclusions

Simple data structure for unit propagation



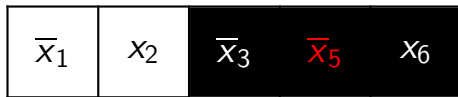
Conflict-driven: Watch pointers (1) [MoskewiczMZZM'01]

$$\varphi = \{x_1 = *, x_2 = *, x_3 = *, x_4 = *, x_5 = *, x_6 = *\}$$



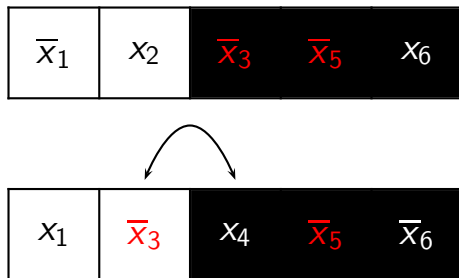
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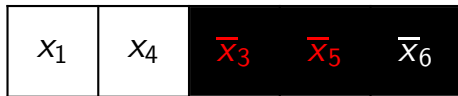
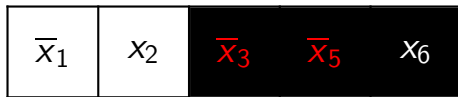
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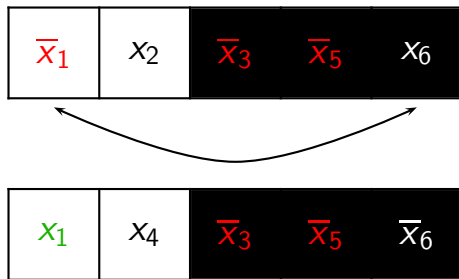
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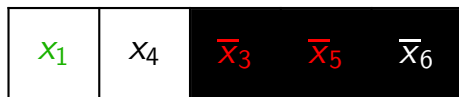
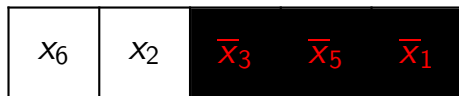
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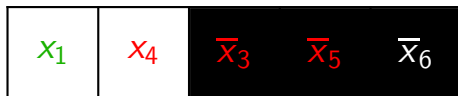
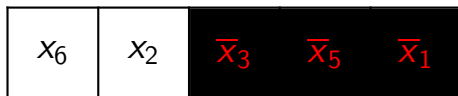
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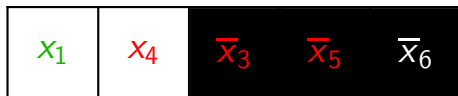
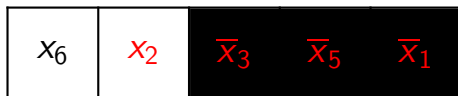
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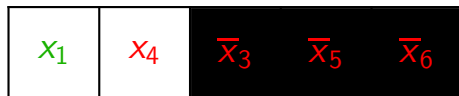
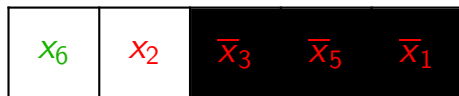
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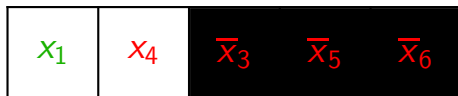
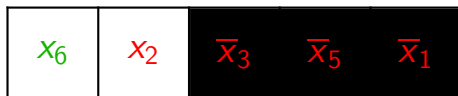
Conflict-driven: Watch pointers (1) [MoskewiczMZZM'01]

$$\varphi = \{x_1 = 1, x_2 = 0, x_3 = 1, x_4 = 0, x_5 = 1, x_6 = \mathbf{1}\}$$



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Conflict-driven: Watch pointers (2) [MoskewiczMZZM'01]

Only examine (get in the cache) a clause when both

- ▶ a watch pointer gets falsified
- ▶ the other one is not satisfied

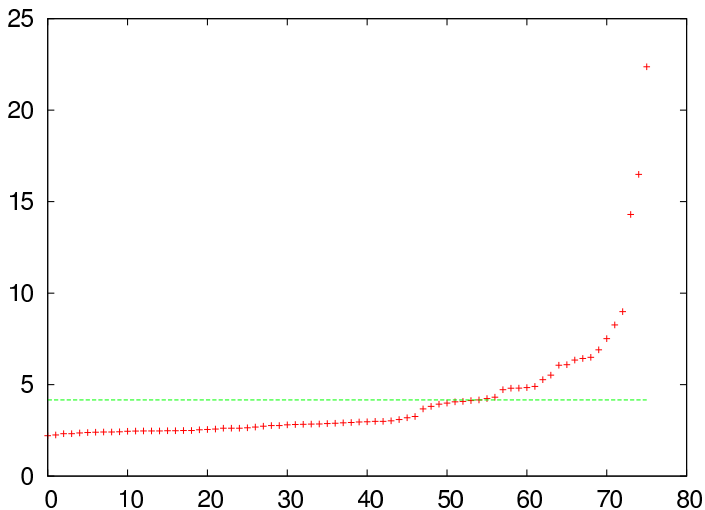
While backjumping, just unassign variables

Conflict clauses \rightarrow watch pointers

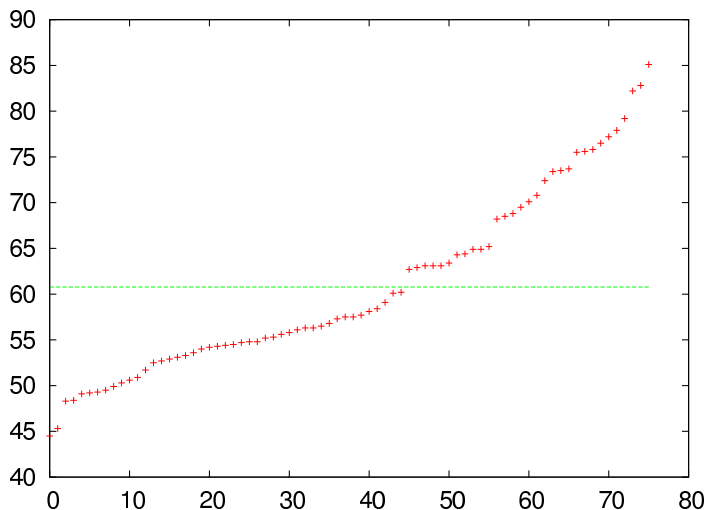
No detailed information available

Not used for binary clauses

Average Number Clauses Visited Per Propagation



Percentage visited clauses with other watched literal true



Clause Learning

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Recent Advances and Conclusions

Most important CDCL heuristics

Variable selection heuristics

- ▶ aim: minimize the search space
- ▶ plus: could compensate a bad value selection

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Restart strategies

- ▶ aim: avoid heavy-tail behavior [GomesSelmanCrato'97]
- ▶ plus: focus search on recent conflicts when combined with dynamic heuristics

Variable selection heuristics

Based on the occurrences in the (reduced) formula

- ▶ examples: Jeroslow-Wang, Maximal Occurrence in clauses of Minimal Size (MOMS), look-aheads
- ▶ not practical for CDCL solver due to watch pointers

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Variable State Independent Decaying Sum (VSIDS)

- ▶ original idea (zChaff): for each conflict, increase the score of involved variables by 1, half all scores each 256 conflicts
[MoskewiczMZZM'01]
- ▶ improvement (MiniSAT): for each conflict, increase the score of involved variables by δ and increase $\delta := 1.05\delta$
[EenSörensson'03]

Visualization of VSIDS in PicoSAT

<http://www.youtube.com/watch?v=M0jhFywLre8>

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- ▶ negative branching (early MiniSAT) [EenSörensson'03]

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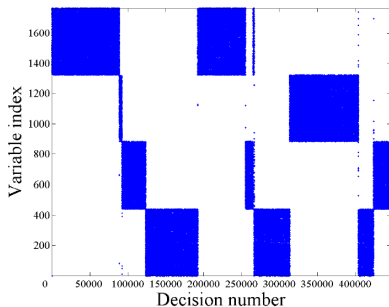
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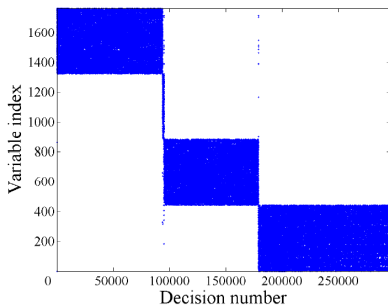
Based on the last implied value (phase-saving)

- ▶ introduced to CDCL [PipatsrisawatDarwiche'07]
- ▶ already used in local search [HirschKojevnikov'01]

Selecting the last implied value remembers solved components



negative branching



phase-saving

Restarts

Restarts in CDCL solvers:

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- ▶ Geometrical restart: e.g. 100, 150, 225, 333, 500, 750, ...
- ▶ Luby sequence: e.g. 100, 100, 200, 100, 100, 200, 400, ...

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Rapid restarts by reusing trail: [vanderTakHeuleRamos'11]

- ▶ Partial restart same effect as full restart
- ▶ Optimal strategy Luby-1: 1, 1, 2, 1, 1, 2, 4, ...

The best heuristics choices depend on satisfiability: E.g.

- ▶ Restart **frequently** for UNSAT instances to get conflict early
- ▶ Restart **sporadically** for SAT instances to keep “progress”

Also, **keeping** learned clauses is **less important** on SAT instances and can actually slow down the search.

State-of-the-art CDCL solvers, such as CaDiCaL, have **separate modes** for SAT and UNSAT and they alternate between them.

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Clause deletion [EenSörensson'03, AudemardSimon'09]

Conflict clauses can significantly **slow down** CDCL solvers:

- ▶ Conflict clauses can quickly **outnumber** the original clauses
- ▶ Conflict clauses consists of **important variables**

Clause deletion is used to reduce the overhead:

- ▶ When the learned clause reach a limit, **remove half**
- ▶ **Increase limit** after every removal (completeness)

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Clause deletion heuristics:

- ▶ **length** of the clause
- ▶ **relevance** of the clause (when was it used in Analyze)
- ▶ the number of **involved decision levels**

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Recent Advances and Conclusions

Self-Subsumption

Use self-subsumption to shorten conflict clauses

$$\frac{C \vee l \quad D \vee \bar{l}}{D} \quad C \subseteq D \quad \frac{(a \vee b \vee l) \quad (a \vee b \vee c \vee \bar{l})}{(a \vee b \vee c)}$$

Conflict clause minimization is an important optimization.

Self-Subsumption

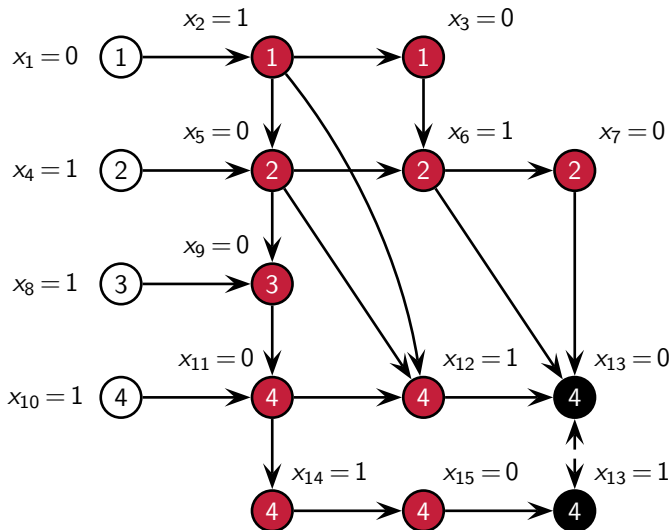
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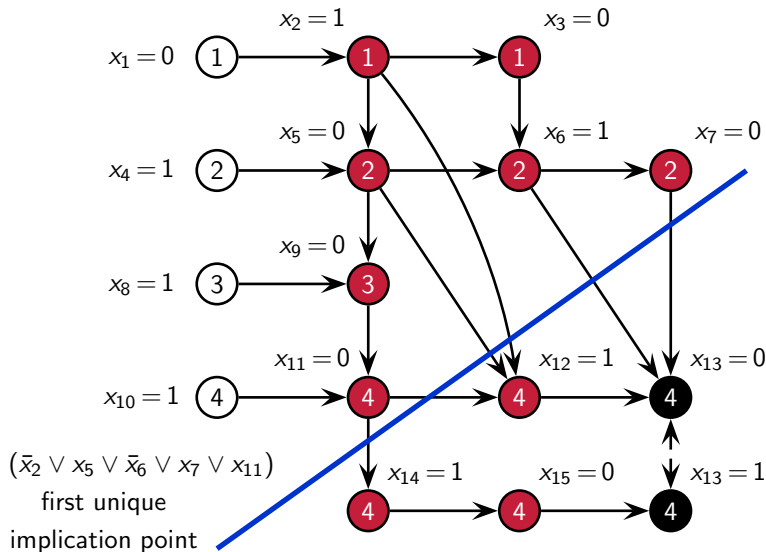
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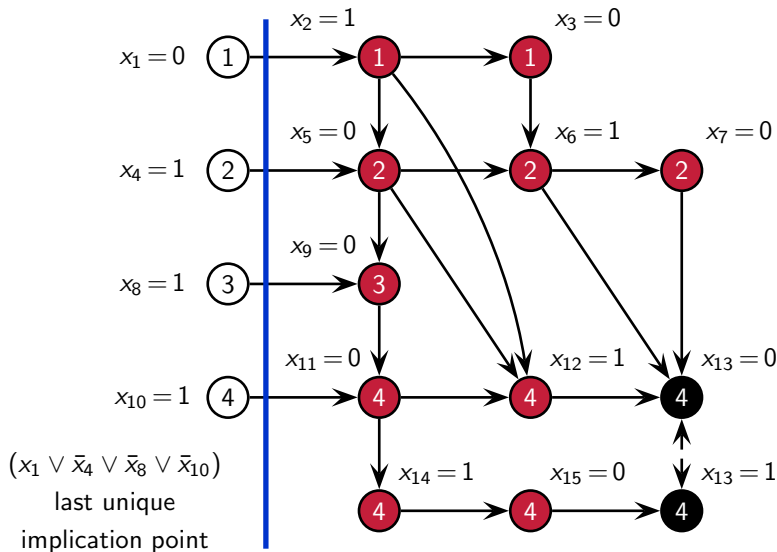
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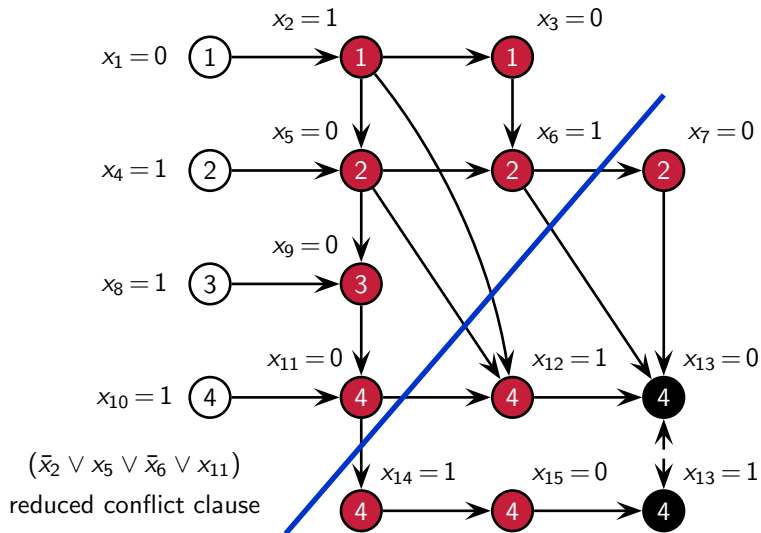
Use implication chains to further minimization:

$$\dots (\bar{a} \vee b)(\bar{b} \vee c)(a \vee c \vee d) \dots \Rightarrow$$
$$\dots (\bar{a} \vee b)(\bar{b} \vee c)(c \vee d) \dots$$



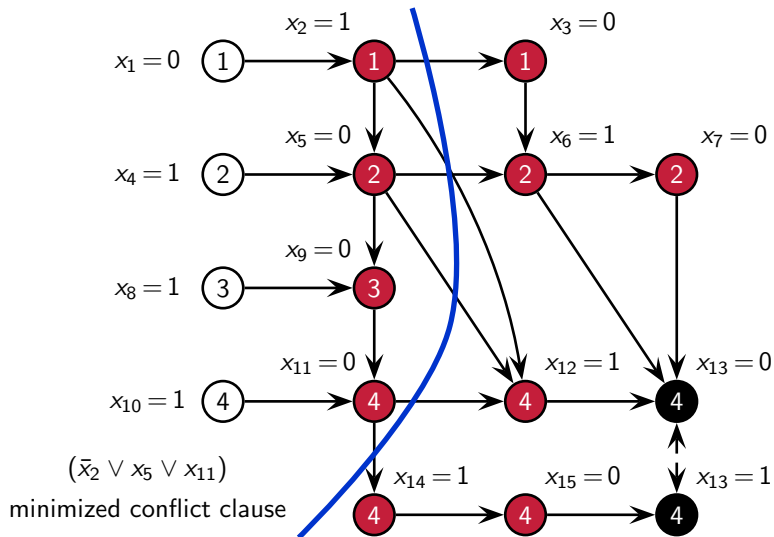






Conflict-clause minimization

[SörenssonBiere'09]



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Recent Advances and Conclusions

Recent Advances

A new idea contributes to **winning the competition**.

Winner 2017: Clause vivification during search

[LuoLiXiaoManyáLü'17]

Winner 2018: Chronological backtracking

[NadelRyvchin'18]

Winner 2019: Multiple learnt clauses per conflict

[KochemazovZaikinKondratievSemenov'19]

Conclusions: state-of-the-art CDCL solver

Key contributions to CDCL solvers:

- ▶ concept of conflict clauses (grasp) [Marques-SilvaSakallah'96]
- ▶ restart strategies [GomesSC'97,LubySZ'93]
- ▶ 2-watch pointers and VSIDS (zChaff) [MoskewiczMZZM'01]
- ▶ efficient implementation (Minisat) [EenSörensson'03]
- ▶ phase-saving (Rsat) [PipatsrisawatDarwiche'07]
- ▶ conflict-clause minimization [SörenssonBiere'09]
- ▶ SAT vs UNSAT [Oh'15]

+ Pre- and in-processing techniques