Formal Methods: Module I: Automated Reasoning Ch. 01: **Reasoning in Propositional Logic**

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Outline

1. Boolean Logics and SAT
2. Basic SAT-Solving Techniques
   - Resolution
   - Tableaux
   - DPLL
   - Stochastic Local Search for SAT
3. Ordered Binary Decision Diagrams – OBDDs
4. Modern CDCL SAT Solvers
   - Limitations of Chronological Backtracking
   - Conflict-Driven Clause-Learning SAT solvers
   - Further Improvements
   - SAT Under Assumptions & Incremental SAT
5. SAT Functionalities: proofs, unsat cores, interpolants, optimization

Outline

Propositional Logic (aka Boolean Logic)

Basic Definitions

- Propositional formula (aka Boolean formula)
  - $\top, \bot$ are formulas
  - a propositional atom $A_1, A_2, A_3, ...$ is a formula;
  - if φ_1 and φ_2 are formulas, then
    $\neg\varphi_1, \varphi_1 \wedge \varphi_2, \varphi_1 \vee \varphi_2, \varphi_1 \rightarrow \varphi_2, \varphi_1 \leftarrow \varphi_2, \varphi_1 \leftrightarrow \varphi_2, \varphi_1 \oplus \varphi_2$
    are formulas.
- Ex: $\varphi \stackrel{\text{def}}{=} (\neg(A_1 \rightarrow A_2)) \wedge (A_3 \leftrightarrow (\neg A_1 \oplus (A_2 \vee \neg A_4))))$
- *Atoms*(φ): the set $\{A_1, ..., A_N\}$ of atoms occurring in φ.
  - Ex: $Atoms(\varphi) = \{A_1, A_2, A_3, A_4\}$
- Literal: a propositional atom A_i (positive literal) or its negation $\neg A_i$ (negative literal)
  - Notation: if $l := \neg A_i$, then $\neg l := A_i$
- Clause: a disjunction of literals $\bigvee_j l_j$ (e.g., $(A_1 \vee \neg A_2 \vee A_3 \vee ...)$)
- Cube: a conjunction of literals $\bigwedge_j l_j$ (e.g., $(A_1 \wedge \neg A_2 \wedge A_3 \wedge ...)$)

Semantics of Boolean operators

Truth Table

α	β	$\neg\alpha$	$\alpha\wedge\beta$	$\alpha\vee\beta$	$\alpha\rightarrow\beta$	$\alpha\leftarrow\beta$	$\alpha\leftrightarrow\beta$	$\alpha\oplus\beta$
$\bot$	$\bot$	$\top$	$\bot$	$\bot$	$\top$	$\top$	$\top$	$\bot$
$\bot$	$\top$	$\top$	$\bot$	$\top$	$\top$	$\bot$	$\bot$	$\top$
$\top$	$\bot$	$\bot$	$\bot$	$\top$	$\bot$	$\top$	$\bot$	$\top$
$\top$	$\top$	$\bot$	$\top$	$\top$	$\top$	$\top$	$\top$	$\bot$

Semantics of Boolean operators (cont.)

Note

- $\wedge$, $\vee$, $\leftrightarrow$ and $\oplus$ are commutative:

$$
\begin{array}{lcl}
(\alpha \wedge \beta) & \Longleftrightarrow & (\beta \wedge \alpha) \\
(\alpha \vee \beta) & \Longleftrightarrow & (\beta \vee \alpha) \\
(\alpha \leftrightarrow \beta) & \Longleftrightarrow & (\beta \leftrightarrow \alpha) \\
(\alpha \oplus \beta) & \Longleftrightarrow & (\beta \oplus \alpha)
\end{array}
$$

- $\wedge$, $\vee$, $\leftrightarrow$ and $\oplus$ are associative:

$$
\begin{array}{lclcl}
((\alpha \wedge \beta) \wedge \gamma) & \Longleftrightarrow & (\alpha \wedge (\beta \wedge \gamma)) & \Longleftrightarrow & (\alpha \wedge \beta \wedge \gamma) \\
((\alpha \vee \beta) \vee \gamma) & \Longleftrightarrow & (\alpha \vee (\beta \vee \gamma)) & \Longleftrightarrow & (\alpha \vee \beta \vee \gamma) \\
((\alpha \leftrightarrow \beta) \leftrightarrow \gamma) & \Longleftrightarrow & (\alpha \leftrightarrow (\beta \leftrightarrow \gamma)) & \Longleftrightarrow & (\alpha \leftrightarrow \beta \leftrightarrow \gamma) \\
((\alpha \oplus \beta) \oplus \gamma) & \Longleftrightarrow & (\alpha \oplus (\beta \oplus \gamma)) & \Longleftrightarrow & (\alpha \oplus \beta \oplus \gamma)
\end{array}
$$

- $\rightarrow$, $\leftarrow$ are neither commutative nor associative:

$$
\begin{array}{lcl}
(\alpha \rightarrow \beta) & \not\Longleftrightarrow & (\beta \rightarrow \alpha) \\
((\alpha \rightarrow \beta) \rightarrow \gamma) & \not\Longleftrightarrow & (\alpha \rightarrow (\beta \rightarrow \gamma))
\end{array}
$$

Remark: Semantics of Implication “$\rightarrow$” (aka “$\Rightarrow$”, “$\supset$”)

The semantics of Implication “$\alpha \rightarrow \beta$” may be counter-intuitive

$\alpha \rightarrow \beta$: “the antecedent (aka premise) α implies the consequent (aka conclusion) β” (aka “if α holds, then β holds” (but not vice versa))

- does not require causation or relevance between α and β
  - ex: “5 is odd implies Tokyo is the capital of Japan” is true in p.l. (under standard interpretation of “5”, “odd”, “Tokyo”, “Japan”)
  - relation between antecedent & consequent: they are both true
- is true whenever its antecedent is false
  - ex: “5 is even implies Sam is smart” is true (regardless the smartness of Sam)
  - ex: “5 is even implies Tokyo is in Italy” is true (!)
  - relation between antecedent & consequent: the former is false
- does not require temporal precedence of α wrt. β
  - ex: “the grass is wet implies it must have rained” is true (the consequent precedes temporally the antecedent)

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Syntactic Properties of Boolean Operators

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(\alpha \rightarrow \beta) & \Longleftrightarrow & (\neg\alpha \vee \beta) \\
\neg(\alpha \rightarrow \beta) & \Longleftrightarrow & (\alpha \wedge \neg\beta) \\
(\alpha \leftarrow \beta) & \Longleftrightarrow & (\alpha \vee \neg\beta) \\
\neg(\alpha \leftarrow \beta) & \Longleftrightarrow & (\neg\alpha \wedge \beta) \\
(\alpha \leftrightarrow \beta) & \Longleftrightarrow & ((\alpha \rightarrow \beta) \wedge (\alpha \leftarrow \beta)) \\
 & \Longleftrightarrow & ((\neg\alpha \vee \beta) \wedge (\alpha \vee \neg\beta)) \\
\neg(\alpha \leftrightarrow \beta) & \Longleftrightarrow & (\neg\alpha \leftrightarrow \beta) \\
 & \Longleftrightarrow & (\alpha \leftrightarrow \neg\beta) \\
 & \Longleftrightarrow & ((\alpha \vee \beta) \wedge (\neg\alpha \vee \neg\beta)) \\
(\alpha \oplus \beta) & \Longleftrightarrow & \neg(\alpha \leftrightarrow \beta)
\end{array}
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Boolean logic can be expressed in terms of $\{\neg, \wedge\}$ (or $\{\neg, \vee\}$) only!

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(\alpha \wedge \beta) & \iff & \neg(\neg\alpha \vee \neg\beta) \\
\neg(\alpha \wedge \beta) & \iff & (\neg\alpha \vee \neg\beta) \\
(\alpha \to \beta) & \iff & (\neg\alpha \vee \beta) \\
\neg(\alpha \to \beta) & \iff & (\alpha \wedge \neg\beta) \\
(\alpha \leftarrow \beta) & \iff & (\alpha \vee \neg\beta) \\
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(\alpha \leftrightarrow \beta) & \iff & ((\alpha \to \beta) \wedge (\alpha \leftarrow \beta)) \\
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 & \iff & ((\alpha \vee \beta) \wedge (\neg\alpha \vee \neg\beta)) \\
(\alpha \oplus \beta) & \iff & \neg(\alpha \leftrightarrow \beta)
\end{array}
$$

Boolean logic can be expressed in terms of $\{\neg, \wedge\}$ (or $\{\neg, \vee\}$) only!

Exercises

1. For every pair of formulas $\alpha \iff \beta$ below, show that α and β can be rewritten into each other by applying the syntactic properties of the previous slide
   - $(A_1 \wedge A_2) \vee A_3 \iff (A_1 \vee A_3) \wedge (A_2 \vee A_3)$
   - $(A_1 \vee A_2) \wedge A_3 \iff (A_1 \wedge A_3) \vee (A_2 \wedge A_3)$
   - $A_1 \rightarrow (A_2 \rightarrow (A_3 \rightarrow A_4)) \iff (A_1 \wedge A_2 \wedge A_3) \rightarrow A_4$
   - $A_1 \rightarrow (A_2 \wedge A_3) \iff (A_1 \rightarrow A_2) \wedge (A_1 \rightarrow A_3)$
   - $(A_1 \vee A_2) \rightarrow A_3 \iff (A_1 \rightarrow A_3) \wedge (A_2 \rightarrow A_3)$
   - $A_1 \oplus A_2 \iff (A_1 \vee A_2) \wedge (\neg A_1 \vee \neg A_2)$
   - $\neg A_1 \leftrightarrow \neg A_2 \iff A_1 \leftrightarrow A_2$
   - $A_1 \leftrightarrow A_2 \leftrightarrow A_3 \iff A_1 \oplus A_2 \oplus A_3$

Tree & DAG Representations of Formulas

- Formulas can be represented either as trees or as DAGS (Directed Acyclic Graphs)
- DAG representation can be up to exponentially smaller
  - in particular, when $\leftrightarrow$'s are involved

$$(A_1 \leftrightarrow A_2) \leftrightarrow (A_3 \leftrightarrow A_4)$$

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$$(A_1 \leftrightarrow A_2) \leftrightarrow (A_3 \leftrightarrow A_4)$$
$$\Downarrow$$
$$(((A_1 \leftrightarrow A_2) \rightarrow (A_3 \leftrightarrow A_4)) \wedge$$
$$((A_3 \leftrightarrow A_4) \rightarrow (A_1 \leftrightarrow A_2)))$$

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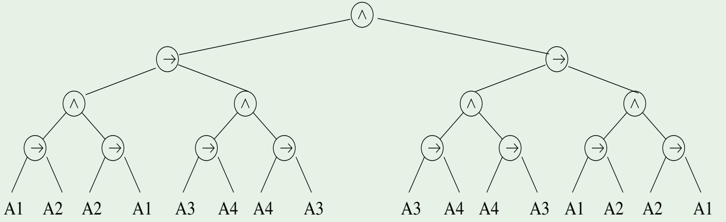
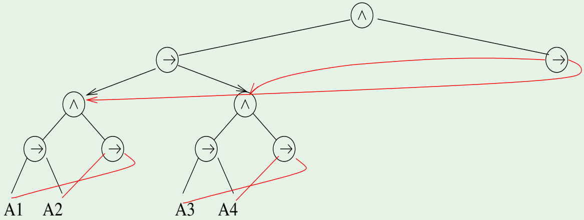
$$\Downarrow$$
$$(((A_1 \rightarrow A_2) \wedge (A_2 \rightarrow A_1)) \rightarrow ((A_3 \rightarrow A_4) \wedge (A_4 \rightarrow A_3))) \wedge$$
$$(((A_3 \rightarrow A_4) \wedge (A_4 \rightarrow A_3)) \rightarrow (((A_1 \rightarrow A_2) \wedge (A_2 \rightarrow A_1))))$$

Tree & DAG Representations of Formulas: Example

$$(((A_1 \to A_2) \land (A_2 \to A_1)) \to ((A_3 \to A_4) \land (A_4 \to A_3))) \land$$
$$(((A_3 \to A_4) \land (A_4 \to A_3)) \to (((A_1 \to A_2) \land (A_2 \to A_1))))$$



Tree Representation



DAG Representation

Semantics: Basic Definitions

- Total truth assignment μ for φ:
  $\mu : Atoms(\varphi) \longmapsto \{\top, \bot\}$.
  - represents a possible world or a possible state of the world
- Partial Truth assignment μ for φ:
  $\mu : \mathcal{A} \longmapsto \{\top, \bot\}$, $\mathcal{A} \subset Atoms(\varphi)$.
  - represents 2^k total assignments, k is $\#$ unassigned variables
- Notation: set and formula representations of an assignment
  - μ can be represented as a set of literals:
    EX: $\{\mu(A_1) := \top, \mu(A_2) := \bot\} \implies \{A_1, \neg A_2\}$
  - μ can be represented as a formula (cube):
    EX: $\{\mu(A_1) := \top, \mu(A_2) := \bot\} \implies (A_1 \wedge \neg A_2)$

Semantics: Basic Definitions [cont.]

- A total truth assignment μ satisfies φ (μ is a model of φ, $\mu \models \varphi$):

$$\mu \models A_i \iff \mu(A_i) = \top$$
$$\mu \models \neg\varphi \iff \textit{not } \mu \models \varphi$$
$$\mu \models \alpha \wedge \beta \iff \mu \models \alpha \textit{ and } \mu \models \beta$$
$$\mu \models \alpha \vee \beta \iff \mu \models \alpha \textit{ or } \mu \models \beta$$
$$\mu \models \alpha \rightarrow \beta \iff \textit{ if } \mu \models \alpha, \textit{ then } \mu \models \beta$$
$$\mu \models \alpha \leftrightarrow \beta \iff \mu \models \alpha \textit{ iff } \mu \models \beta$$
$$\mu \models \alpha \oplus \beta \iff \mu \models \alpha \textit{ iff not } \mu \models \beta$$

- $M(\varphi) \stackrel{\text{def}}{=} \{\mu \mid \mu \models \varphi\}$ (the set of models of φ)
- A partial truth assignment μ satisfies φ iff all total assignments extending μ satisfy φ
  - Ex: $\{A_1\} \models (A_1 \vee A_2))$ because both $\{A_1, A_2\} \models (A_1 \vee A_2)$ and $\{A_1, \neg A_2\} \models (A_1 \vee A_2)$
- φ is satisfiable iff $\mu \models \varphi$ for some μ (i.e. $M(\varphi) \neq \emptyset$)
- α entails β ($\alpha \models \beta$): $\alpha \models \beta$ iff $\mu \models \alpha \Longrightarrow \mu \models \beta$ for all μs (i.e., $M(\alpha) \subseteq M(\beta)$)
- φ is valid ($\models \varphi$): $\models \varphi$ iff $\mu \models \varphi$ forall μs (i.e., $\mu \in M(\varphi)$ forall μs)

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Properties & Results

Property

φ is valid iff $\neg\varphi$ is not satisfiable

Deduction Theorem

$\alpha \models \beta$ iff $\alpha \rightarrow \beta$ is valid ($\models \alpha \rightarrow \beta$)

Corollary

$\alpha \models \beta$ iff $\alpha \wedge \neg\beta$ is not satisfiable

Validity and entailment checking can be straightforwardly reduced to (un)satisfiability checking!

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Corollary

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Equivalence and Equi-Satisfiability

- α and β are equivalent iff, for every μ, $\mu \models \alpha$ iff $\mu \models \beta$ (i.e., if $M(\alpha) = M(\beta)$)
- α and β are equi-satisfiable iff exists μ_1 s.t. $\mu_1 \models \alpha$ iff exists μ_2 s.t. $\mu_2 \models \beta$ (i.e., if $M(\alpha) \neq \emptyset$ iff $M(\beta) \neq \emptyset$)
- α, β equivalent

  $\Downarrow \quad \not\Uparrow$

  α, β equi-satisfiable
- EX: $A_1 \vee A_2$ and $(A_1 \vee \neg A_3) \wedge (A_3 \vee A_2)$ are equi-satisfiable, not equivalent.

  $\{\neg A_1, A_2, A_3\} \models (A_1 \vee A_2)$, but

  $\{\neg A_1, A_2, A_3\} \not\models (A_1 \vee \neg A_3) \wedge (A_3 \vee A_2)$
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Equivalence and Equi-Satisfiability

- α and β are equivalent iff, for every μ, $\mu \models \alpha$ iff $\mu \models \beta$ (i.e., if $M(\alpha) = M(\beta)$)
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Complexity

- For N variables, there are up to 2^N truth assignments to be checked.
- The problem of deciding the satisfiability of a propositional formula is NP-complete

$\Longrightarrow$ The most important logical problems (validity, inference, entailment, equivalence, ...) can be straightforwardly reduced to (un)satisfiability, and are thus (co)NP-complete.

$$\Downarrow$$

No existing worst-case-polynomial algorithm.

POLARITY of subformulas

Polarity: the number of nested negations modulo 2.

- Positive/negative occurrences
  - φ occurs positively in φ;
  - if $\neg\varphi_1$ occurs positively [negatively] in φ, then φ_1 occurs negatively [positively] in φ
  - if $\varphi_1 \wedge \varphi_2$ or $\varphi_1 \vee \varphi_2$ occur positively [negatively] in φ, then φ_1 and φ_2 occur positively [negatively] in φ;
  - if $\varphi_1 \rightarrow \varphi_2$ occurs positively [negatively] in φ, then φ_1 occurs negatively [positively] in φ and φ_2 occurs positively [negatively] in φ;
  - if $\varphi_1 \leftrightarrow \varphi_2$ or $\varphi_1 \oplus \varphi_2$ occurs in φ, then φ_1 and φ_2 occur positively and negatively in φ;

Negative Normal Form (NNF)

- φ is in Negative normal form iff it is given only by the recursive applications of $\wedge, \vee$ to literals.
- every φ can be reduced into NNF:
  (i) substituting all $\rightarrow$'s and $\leftrightarrow$'s:

$$\begin{array}{lll} \alpha \rightarrow \beta & \Longrightarrow & \neg\alpha \vee \beta \\ \alpha \leftrightarrow \beta & \Longrightarrow & (\neg\alpha \vee \beta) \wedge (\alpha \vee \neg\beta) \end{array}$$

  (ii) pushing down negations recursively:

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$$(A_1 \leftrightarrow A_2) \leftrightarrow (A_3 \leftrightarrow A_4)$$

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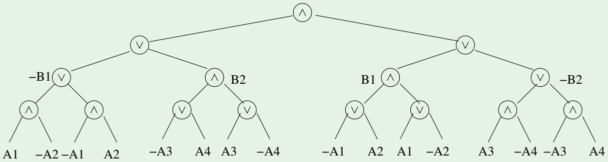
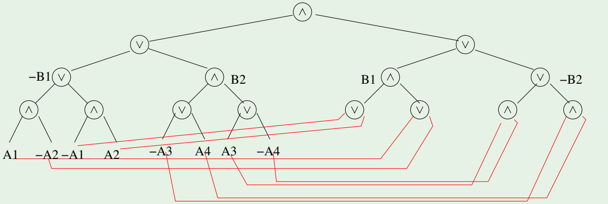
NNF: Example [cont.]

Note



Tree Representation



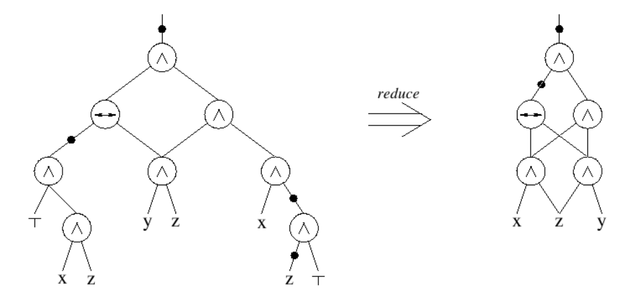
DAG Representation

For each non-literal subformula φ, φ and $\neg\varphi$ have different representations $\Longrightarrow$ they are not shared.

Optimized polynomial representations

And-Inverter Graphs, Reduced Boolean Circuits, Boolean Expression Diagrams

- Maximize the sharing in DAG representations: $\{\wedge, \leftrightarrow, \neg\}$-only, negations on arcs, sorting of subformulae, lifting of $\neg$'s over $\leftrightarrow$'s,...



Conjunctive Normal Form (CNF)

- φ is in Conjunctive normal form iff it is a conjunction of disjunctions of literals:

$$\bigwedge_{i=1}^{L} \bigvee_{j_i=1}^{K_i} l_{j_i}$$

- the disjunctions of literals $\bigvee_{j_i=1}^{K_i} l_{j_i}$ are called clauses
- Easier to handle: list of lists of literals.
  $\Longrightarrow$ no reasoning on the recursive structure of the formula

Classic CNF Conversion $CNF(\varphi)$

- Every φ can be reduced into CNF by, e.g.,
  (i) expanding implications and equivalences:
  $$\alpha \rightarrow \beta \implies \neg\alpha \vee \beta$$
  $$\alpha \leftrightarrow \beta \implies (\neg\alpha \vee \beta) \wedge (\alpha \vee \neg\beta)$$
  (ii) pushing down negations recursively:
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  $$(\alpha \wedge \beta) \vee \gamma \implies (\alpha \vee \gamma) \wedge (\beta \vee \gamma)$$
- Resulting formula worst-case exponential:
  - ex: $||\text{CNF}(\bigvee_{i=1}^{N}(l_{i1} \wedge l_{i2})|| =$
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- Every φ can be reduced into CNF by, e.g., applying recursively bottom-up the rules:

$$\varphi \implies \varphi[(l_i \vee l_j)|B] \wedge CNF(B \leftrightarrow (l_i \vee l_j))$$
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- Worst-case linear!
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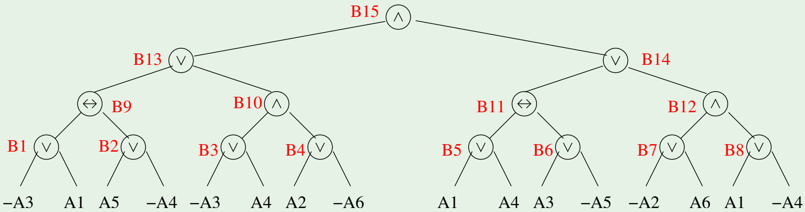
Labeling CNF conversion $CNF_{label}(\varphi)$ (cont.)

$CNF(B \leftrightarrow (l_i \vee l_j))$	$\Longleftrightarrow$	$(\neg B \vee l_i \vee l_j) \wedge$ $(B \vee \neg l_i) \wedge$ $(B \vee \neg l_j)$
$CNF(B \leftrightarrow (l_i \wedge l_j))$	$\Longleftrightarrow$	$(\neg B \vee l_i) \wedge$ $(\neg B \vee l_j) \wedge$ $(B \vee \neg l_i \neg l_j)$
$CNF(B \leftrightarrow (l_i \leftrightarrow l_j))$	$\Longleftrightarrow$	$(\neg B \vee \neg l_i \vee l_j) \wedge$ $(\neg B \vee l_i \vee \neg l_j) \wedge$ $(B \vee l_i \vee l_j) \wedge$ $(B \vee \neg l_i \vee \neg l_j)$

Labeling CNF Conversion CNF_{label} – Example



$$
\begin{array}{lcl}
CNF(B_1 \leftrightarrow (\neg A_3 \vee A_1))\wedge & & (\neg B_1 \vee \neg A_3 \vee A_1) \wedge (B_1 \vee A_3) \wedge (B_1 \vee \neg A_1)\wedge \\
\ldots\wedge & & \ldots\wedge \\
CNF(B_8 \leftrightarrow (A_1 \vee \neg A_4))\wedge & & (\neg B_8 \vee A_1 \vee \neg A_4) \wedge (B_8 \vee \neg A_1) \wedge (B_8 \vee A_4)\wedge \\
CNF(B_9 \leftrightarrow (B_1 \leftrightarrow B_2))\wedge & & (\neg B_9 \vee \neg B_1 \vee B_2) \wedge (\neg B_9 \vee B_1 \vee \neg B_2)\wedge \\
 & & (B_9 \vee B_1 \vee B_2) \wedge (B_9 \vee \neg B_1 \vee \neg B_2)\wedge \\
\ldots\wedge & = & \ldots\wedge \\
CNF(B_{12} \leftrightarrow (B_7 \wedge B_8))\wedge & & (B_{12} \vee \neg B_7 \vee \neg B_8) \wedge (\neg B_{12} \vee B_7) \wedge (\neg B_{12} \vee B_8)\wedge \\
CNF(B_{13} \leftrightarrow (B_9 \vee B_{10}))\wedge & & (\neg B_{13} \vee B_9 \vee B_{10}) \wedge (B_{13} \vee \neg B_9) \wedge (B_{13} \vee \neg B_{10})\wedge \\
CNF(B_{14} \leftrightarrow (B_{11} \vee B_{12}))\wedge & & (\neg B_{14} \vee B_{11} \vee B_{12}) \wedge (B_{14} \vee \neg B_{11}) \wedge (B_{14} \vee \neg B_{12})\wedge \\
CNF(B_{15} \leftrightarrow (B_{13} \wedge B_{14}))\wedge & & (B_{15} \vee \neg B_{13} \vee \neg B_{14}) \wedge (\neg B_{15} \vee B_{13}) \wedge (\neg B_{15} \vee B_{14})\wedge \\
B_{15} & & B_{15}
\end{array}
$$

Labeling CNF conversion CNF_{label} (improved)

- As in the previous case, applying instead the rules:

$$
\begin{array}{llll}
\varphi & \Longrightarrow & \varphi[(l_i \vee l_j)|B] & \wedge\ CNF(B \rightarrow (l_i \vee l_j)) & \text{if } (l_i \vee l_j) \text{ pos.}\\
\varphi & \Longrightarrow & \varphi[(l_i \vee l_j)|B] & \wedge\ CNF((l_i \vee l_j) \rightarrow B) & \text{if } (l_i \vee l_j) \text{ neg.}\\
\varphi & \Longrightarrow & \varphi[(l_i \wedge l_j)|B] & \wedge\ CNF(B \rightarrow (l_i \wedge l_j)) & \text{if } (l_i \wedge l_j) \text{ pos.}\\
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\end{array}
$$

- Smaller in size:

$$
\begin{array}{ll}
CNF(B \rightarrow (l_i \vee l_j)) & = (\neg B \vee l_i \vee l_j)\\
CNF(((l_i \vee l_j) \rightarrow B)) & = (\neg l_i \vee B) \wedge (\neg l_j \vee B)
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Labeling CNF conversion $CNF_{label}(\varphi)$ (cont.)

$CNF(B \rightarrow (l_i \vee l_j))$	$\Longleftrightarrow$	$(\neg B \vee l_i \vee l_j)$
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$CNF(B \rightarrow (l_i \wedge l_j))$	$\Longleftrightarrow$	$(\neg B \vee l_i) \wedge$ $(\neg B \vee l_j)$
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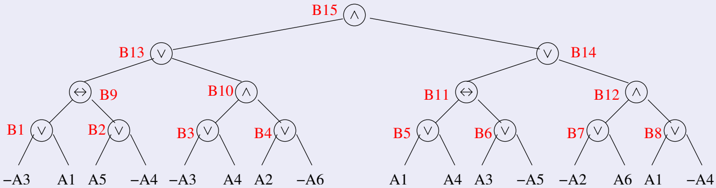
Labeling CNF conversion CNF_{label} – example



Basic

$$
\begin{array}{ll}
CNF(B_1 \leftrightarrow (\neg A_3 \vee A_1)) & \wedge \\
\ldots & \wedge \\
CNF(B_8 \leftrightarrow (A_1 \vee \neg A_4)) & \wedge \\
CNF(B_9 \leftrightarrow (B_1 \leftrightarrow B_2)) & \wedge \\
\ldots & \wedge \\
CNF(B_{12} \leftrightarrow (B_7 \wedge B_8)) & \wedge \\
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CNF(B_{15} \leftrightarrow (B_{13} \wedge B_{14})) & \wedge \\
B_{15} &
\end{array}
$$

Improved

$$
\begin{array}{ll}
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\ldots & \wedge \\
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B_{15} &
\end{array}
$$

Labeling CNF conversion CNF_{label} – optimizations

- Do not apply CNF_{label} when not necessary:
  (e.g., $CNF_{label}(\varphi_1 \wedge \varphi_2) \Longrightarrow CNF_{label}(\varphi_1) \wedge \varphi_2$,
  if φ_2 already in CNF)
- Apply DeMorgan's rules where it is more effective: (e.g.,
  $CNF_{label}(\varphi_1 \wedge (A \rightarrow (B \wedge C))) \Longrightarrow CNF_{label}(\varphi_1) \wedge (\neg A \vee B) \wedge (\neg A \vee C)$
- exploit the associativity of $\wedge$'s and $\vee$'s:
  $$...\underbrace{(A_1 \vee (A_2 \vee A_3))}_{B}... \Longrightarrow ...CNF(B \leftrightarrow (A_1 \vee A_2 \vee A_3))...$$
- before applying CNF_{label}, rewrite the initial formula so that to maximize the sharing of subformulas (RBC, BED)
- ...

Exercises

1. Consider the following Boolean formula φ:
   $\neg(((\neg A_1 \rightarrow A_2) \wedge (\neg A_3 \rightarrow A_4)) \vee ((A_5 \rightarrow A_6) \wedge (A_7 \rightarrow \neg A_8)))$
   Compute the Negative Normal Form of φ
2. Consider the following Boolean formula φ:
   $((\neg A_1 \wedge A_2) \vee (A_7 \wedge A_4) \vee (\neg A_3 \wedge \neg A_2) \vee (A_5 \wedge \neg A_4))$
   1. Produce the CNF formula $CNF(\varphi)$.
   2. Produce the CNF formula $CNF_{label}(\varphi)$.
   3. Produce the CNF formula $CNF_{label}(\varphi)$ (improved version)

Outline

Propositional Reasoning: Generalities

- Automated Reasoning in Propositional Logic fundamental task
  - AI, formal verification, circuit synthesis, operational research,....
- Important in AI: $KB \models \alpha$: entail fact α from knowledge base KR (aka Model Checking: $M(KB) \subseteq M(\alpha)$)
  - typically $KB >> \alpha$
- All propositional reasoning tasks reduced to satisfiability (SAT)
  - $KR \models \alpha \Longrightarrow$ SAT($KR \wedge \neg\alpha$)=false
  - input formula CNF-ized and fed to a SAT solver
- Current SAT solvers dramatically efficient:
  - handle industrial problems with $10^6 - 10^7$ variables & clauses!
  - used as backend engines in a variety of systems

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Truth Tables

- Exhaustive evaluation of all subformulas:

φ_1	φ_2	$\varphi_1 \wedge \varphi_2$	$\varphi_1 \vee \varphi_2$	$\varphi_1 \rightarrow \varphi_2$	$\varphi_1 \leftrightarrow \varphi_2$
$\bot$	$\bot$	$\bot$	$\bot$	$\top$	$\top$
$\bot$	$\top$	$\bot$	$\top$	$\top$	$\bot$
$\top$	$\bot$	$\bot$	$\top$	$\bot$	$\bot$
$\top$	$\top$	$\top$	$\top$	$\top$	$\top$

- Requires polynomial space (draw one line at a time).
- Requires analyzing $2^{|Atoms(\varphi)|}$ lines.
- Never used in practice.

Outline

The Resolution Rule

- Resolution: deduction of a new clause from a pair of clauses with exactly one incompatible variable (resolvent):

$$\frac{(\overbrace{l_1 \vee ... \vee l_k}^{common} \vee \overbrace{l}^{resolvent} \vee \overbrace{l'_{k+1} \vee ... \vee l'_m}^{C'}) \qquad (\overbrace{l_1 \vee ... \vee l_k}^{common} \vee \overbrace{\neg l}^{resolvent} \vee \overbrace{l''_{k+1} \vee ... \vee l''_n}^{C''})}{(\underbrace{l_1 \vee ... \vee l_k}_{common} \vee \underbrace{l'_{k+1} \vee ... \vee l'_m}_{C'} \vee \underbrace{l''_{k+1} \vee ... \vee l''_n}_{C''})}$$

- Ex: $\dfrac{(A \vee B \vee C \vee D \vee E) \qquad (A \vee B \vee \neg C \vee F)}{(A \vee B \vee D \vee E \vee F)}$

- Note: many standard inference rules subcases of resolution: (recall that $\alpha \rightarrow \beta \Longleftrightarrow \neg\alpha \vee \beta$)

$$\frac{A \rightarrow B \quad B \rightarrow C}{A \rightarrow C}(trans.) \qquad \frac{A \quad A \rightarrow B}{B}(m.\ ponens) \qquad \frac{\neg B \quad A \rightarrow B}{\neg A}(m.\ tollens)$$

The Resolution Rule

- **Resolution**: deduction of a new clause from a pair of clauses with exactly one incompatible variable (resolvent):

$$\frac{(\overbrace{l_1 \vee ... \vee l_k}^{common} \vee \overbrace{l}^{resolvent} \vee \overbrace{l'_{k+1} \vee ... \vee l'_m}^{C'}) \qquad (\overbrace{l_1 \vee ... \vee l_k}^{common} \vee \overbrace{\neg l}^{resolvent} \vee \overbrace{l''_{k+1} \vee ... \vee l''_n}^{C''})}{(\underbrace{l_1 \vee ... \vee l_k}_{common} \vee \underbrace{l'_{k+1} \vee ... \vee l'_m}_{C'} \vee \underbrace{l''_{k+1} \vee ... \vee l''_n}_{C''})}$$

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Improvements: Subsumption & Unit Propagation

Alternative "set" notation (Γ clause set):

$$\frac{\Gamma, \phi_1, ..\phi_n}{\Gamma, \phi'_1, ..\phi'_{n'}} \quad \left(e.g., \frac{\Gamma, C_1 \vee p, C_2 \vee \neg p}{\Gamma, C_1 \vee p, C_2 \vee \neg p, C_1 \vee C_2,} \right)$$

- Clause Subsumption (C clause):
$$\frac{\Gamma \wedge C \wedge (C \vee \bigvee_i l_i)}{\Gamma \wedge (C)}$$
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- Unit Subsumption:
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- Unit Propagation = Unit Resolution + Unit Subsumption

"Deterministic" rule: applied before other "non-deterministic" rules!

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Basic Propositional Inference: Resolution [33, 10]

- Assume input formula in CNF
  - if not, apply Tseitin CNF-ization first

$\Longrightarrow$ φ is represented as a set of clauses

- Search for a refutation of φ (is φ unsatisfiable?)
  - recall: $\alpha \models \beta$ iff $\alpha \wedge \neg\beta$ unsatisfiable
- Basic idea: apply iteratively the resolution rule to pairs of clauses with a conflicting literal, producing novel clauses, until either
  - a false clause is generated, or
  - the resolution rule is no more applicable
- Correct: if returns an empty clause, then φ unsat ($\alpha \models \beta$)
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- Time-inefficient
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  - recall: $\alpha \models \beta$ iff $\alpha \wedge \neg\beta$ unsatisfiable
- Basic idea: apply iteratively the resolution rule to pairs of clauses with a conflicting literal, producing novel clauses, until either
  - a false clause is generated, or
  - the resolution rule is no more applicable
- Correct: if returns an empty clause, then φ unsat ($\alpha \models \beta$)
- Complete: if φ unsat ($\alpha \models \beta$), then it returns an empty clause
- Time-inefficient
- Very Memory-inefficient (exponential in memory)
- Many different strategies

Basic Propositional Inference: Resolution [33, 10]

- Assume input formula in CNF
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Resolution: basic strategy [10]

```
function DP(Γ)
    if ⊥ ∈ Γ                                          /* unsat */
        then return False;
    if (Resolve() is no more applicable to Γ)         /* sat     */
        then return True;
    if {a unit clause (l) occurs in Γ}                /* unit    */
        then Γ := Unit_Propagate(l, Γ));
        return  DP(Γ)
    A := select-variable(Γ);                          /* resolve */
    Γ = Γ ∪ ⋃_{A∈C′,¬A∈C″}{Resolve(C′, C″)} \ ⋃_{A∈C′,¬A∈C″}{C′, C″}};
    return  DP(Γ)
```

Hint: drops one variable $A \in Atoms(\Gamma)$ at a time

Resolution: Examples

$$(A_1 \vee A_2) \;\; (A_1 \vee \neg A_2) \;\; (\neg A_1 \vee A_2) \;\; (\neg A_1 \vee \neg A_2)$$

$$\Downarrow$$

$$(A_2) \;\; (A_2 \vee \neg A_2) \;\; (\neg A_2 \vee A_2) \;\; (\neg A_2)$$

$$\Downarrow$$

$$\bot$$

$\Longrightarrow$ UNSAT

Resolution: Examples

$$(A_1 \vee A_2)\ (A_1 \vee \neg A_2)\ (\neg A_1 \vee A_2)\ (\neg A_1 \vee \neg A_2)$$

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Resolution: Examples

$$(A_1 \lor A_2) \;\; (A_1 \lor \neg A_2) \;\; (\neg A_1 \lor A_2) \;\; (\neg A_1 \lor \neg A_2)$$

$$\Downarrow$$

$$(A_2) \;\; (A_2 \lor \neg A_2) \;\; (\neg A_2 \lor A_2) \;\; (\neg A_2)$$

$$\Downarrow$$

$$\bot$$

$\Longrightarrow$ UNSAT

Resolution: Examples (cont.)

$$(A \lor B \lor C) \;\; (B \lor \neg C \lor \neg F) \;\; (\neg B \lor E)$$

$$\Downarrow$$

$$(A \lor C \lor E) \;\; (\neg C \lor \neg F \lor E)$$

$$\Downarrow$$

$$(A \lor E \lor \neg F)$$

$\Longrightarrow$ SAT

Resolution: Examples (cont.)

$$(A \vee B \vee C) \;\; (B \vee \neg C \vee \neg F) \;\; (\neg B \vee E)$$

$$\Downarrow$$

$$(A \vee C \vee E) \;\; (\neg C \vee \neg F \vee E)$$

$$\Downarrow$$

$$(A \vee E \vee \neg F)$$

$\Longrightarrow$ SAT

Resolution: Examples (cont.)

$$(A \vee B \vee C) \;\; (B \vee \neg C \vee \neg F) \;\; (\neg B \vee E)$$

$$\Downarrow$$

$$(A \vee C \vee E) \;\; (\neg C \vee \neg F \vee E)$$

$$\Downarrow$$

$$(A \vee E \vee \neg F)$$

$\Longrightarrow$ SAT

Resolution: Examples (cont.)

$$(A \vee B \vee C) \;\; (B \vee \neg C \vee \neg F) \;\; (\neg B \vee E)$$

$$\Downarrow$$

$$(A \vee C \vee E) \;\; (\neg C \vee \neg F \vee E)$$

$$\Downarrow$$

$$(A \vee E \vee \neg F)$$

$\Longrightarrow$ SAT

Resolution: Examples

$(A \vee B)\ (A \vee \neg B)\ (\neg A \vee C)\ (\neg A \vee \neg C)$

$\Downarrow$

$(A)\ (\neg A \vee C)\ (\neg A \vee \neg C)$

$\Downarrow$

$(C)\ (\neg C)$

$\Downarrow$

$\bot$

$\Longrightarrow$ UNSAT

Resolution: Examples

$$(A \vee B) \;\; (A \vee \neg B) \;\; (\neg A \vee C) \;\; (\neg A \vee \neg C)$$

$$\Downarrow$$

$$(A) \;\; (\neg A \vee C) \;\; (\neg A \vee \neg C)$$

$$\Downarrow$$

$$(C) \;\; (\neg C)$$

$$\Downarrow$$

$$\bot$$

$\Longrightarrow$ UNSAT

Resolution: Examples

$$(A \vee B)\ \ (A \vee \neg B)\ \ (\neg A \vee C)\ \ (\neg A \vee \neg C)$$
$$\Downarrow$$
$$(A)\ \ (\neg A \vee C)\ \ (\neg A \vee \neg C)$$
$$\Downarrow$$
$$(C)\ \ (\neg C)$$
$$\Downarrow$$
$$\bot$$

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Resolution: Examples

$$(A \vee B)\ \ (A \vee \neg B)\ \ (\neg A \vee C)\ \ (\neg A \vee \neg C)$$
$$\Downarrow$$
$$(A)\ \ (\neg A \vee C)\ \ (\neg A \vee \neg C)$$
$$\Downarrow$$
$$(C)\ \ (\neg C)$$
$$\Downarrow$$
$$\bot$$

$\Longrightarrow$ UNSAT

Resolution – summary

- Requires CNF
- Γ may blow up
  $\Longrightarrow$ May require exponential space
- Not very much used in Boolean reasoning (unless integrated with DPLL procedure in recent implementations)

Outline

Semantic tableaux [39]

- Search for an assignment satisfying φ
- applies recursively elimination rules to the connectives
- If a branch contains A_i and $\neg A_i$, (ψ_i and $\neg\psi_i$) for some i, the branch is closed, otherwise it is open.
- if no rule can be applied to an open branch μ, then $\mu \models \varphi$;
- if all branches are closed, the formula is not satisfiable;

Tableau elimination rules

$$\frac{\varphi_1 \wedge \varphi_2}{\begin{array}{c}\varphi_1\\ \varphi_2\end{array}} \qquad \frac{\neg(\varphi_1 \vee \varphi_2)}{\begin{array}{c}\neg\varphi_1\\ \neg\varphi_2\end{array}} \qquad \frac{\neg(\varphi_1 \rightarrow \varphi_2)}{\begin{array}{c}\varphi_1\\ \neg\varphi_2\end{array}} \qquad (\wedge\text{-elimination})$$

$$\frac{\neg\neg\varphi}{\varphi} \qquad (\neg\neg\text{-elimination})$$

$$\frac{\varphi_1 \vee \varphi_2}{\varphi_1 \qquad \varphi_2} \qquad \frac{\neg(\varphi_1 \wedge \varphi_2)}{\neg\varphi_1 \qquad \neg\varphi_2} \qquad \frac{\varphi_1 \rightarrow \varphi_2}{\neg\varphi_1 \qquad \varphi_2} \qquad (\vee\text{-elimination})$$

$$\frac{\varphi_1 \leftrightarrow \varphi_2}{\begin{array}{cc}\varphi_1 & \neg\varphi_1\\ \varphi_2 & \neg\varphi_2\end{array}} \qquad \frac{\neg(\varphi_1 \leftrightarrow \varphi_2)}{\begin{array}{cc}\varphi_1 & \neg\varphi_1\\ \neg\varphi_2 & \varphi_2\end{array}} \qquad (\leftrightarrow\text{-elimination}).$$

Semantic Tableaux – Example

$$\varphi = (A_1 \vee A_2) \wedge (A_1 \vee \neg A_2) \wedge (\neg A_1 \vee A_2) \wedge (\neg A_1 \vee \neg A_2)$$

Semantic Tableaux – Example

$$\varphi = (A_1 \vee A_2) \wedge (A_1 \vee \neg A_2) \wedge (\neg A_1 \vee A_2) \wedge (\neg A_1 \vee \neg A_2)$$

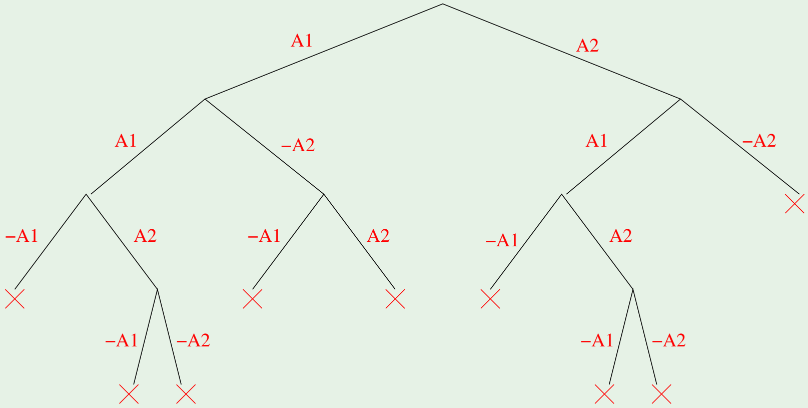


Tableau algorithm

```
function Tableau(Γ)
    if A_i ∈ Γ and ¬A_i ∈ Γ                                  /* branch closed */
        then return False;
    if (φ1 ∧ φ2) ∈ Γ                                         /* ∧-elimination */
        then return Tableau(Γ ∪ {φ1, φ2}\{(φ1 ∧ φ2)});
    if (¬¬φ1) ∈ Γ                                            /* ¬¬-elimination */
        then return Tableau(Γ ∪ {φ1}\{(¬¬φ1)});
    if (φ1 ∨ φ2) ∈ Γ                                         /* ∨-elimination */
        then return   Tableau(Γ ∪ {φ1}\{(φ1 ∨ φ2)})  or
                      Tableau(Γ ∪ {φ2}\{(φ1 ∨ φ2)});
    ...
    return True;                                             /* branch expanded */
```

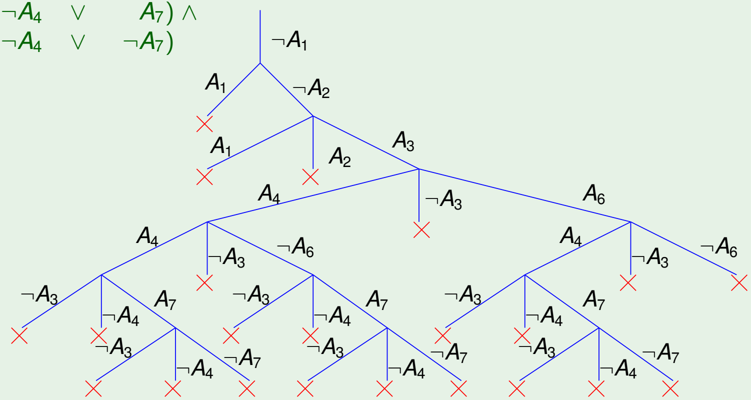
Semantic Tableaux: Example

$$
\begin{array}{rcrcrl}
 & & & & (\neg A_1) & \wedge \\
 & & (\ A_1 & \vee & \neg A_2) & \wedge \\
(\ A_1 & \vee & A_2 & \vee & A_3) & \wedge \\
(\ A_4 & \vee & \neg A_3 & \vee & A_6) & \wedge \\
(\ A_4 & \vee & \neg A_3 & \vee & \neg A_6) & \wedge \\
(\neg A_3 & \vee & \neg A_4 & \vee & A_7) & \wedge \\
(\neg A_3 & \vee & \neg A_4 & \vee & \neg A_7) &
\end{array}
$$

$\Longrightarrow$ unsat

Semantic Tableaux: Example

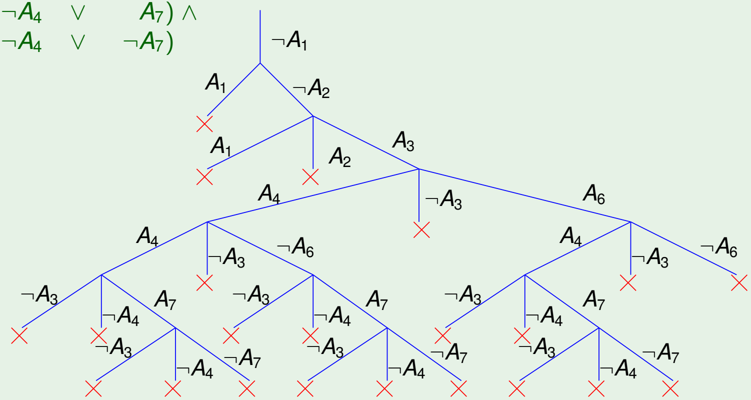
$$
\begin{array}{lllll}
 & & & & (\neg A_1) \wedge \\
 & & (\; A_1 & \vee & \neg A_2) \wedge \\
(\; A_1 & \vee & A_2 & \vee & A_3) \wedge \\
(\; A_4 & \vee & \neg A_3 & \vee & A_6) \wedge \\
(\; A_4 & \vee & \neg A_3 & \vee & \neg A_6) \wedge \\
(\neg A_3 & \vee & \neg A_4 & \vee & A_7) \wedge \\
(\neg A_3 & \vee & \neg A_4 & \vee & \neg A_7)
\end{array}
$$



$\Longrightarrow$ unsat

Semantic Tableaux: Example

$$
\begin{array}{ccccccl}
 & & & & & (\neg A_1) & \wedge \\
 & & (& A_1 & \vee & \neg A_2) & \wedge \\
(& A_1 & \vee & A_2 & \vee & A_3) & \wedge \\
(& A_4 & \vee & \neg A_3 & \vee & A_6) & \wedge \\
(& A_4 & \vee & \neg A_3 & \vee & \neg A_6) & \wedge \\
(& \neg A_3 & \vee & \neg A_4 & \vee & A_7) & \wedge \\
(& \neg A_3 & \vee & \neg A_4 & \vee & \neg A_7) &
\end{array}
$$



$\Longrightarrow$ unsat

Semantic Tableaux – Summary

- Handles all propositional formulas (CNF not required).
- Branches on disjunctions
- Intuitive, modular, easy to extend
  $\Longrightarrow$ loved by logicians.
- Rather inefficient
  $\Longrightarrow$ avoided by computer scientists.
- Requires polynomial space

Outline

DPLL [10, 9]

- Davis-Putnam-Longeman-Loveland procedure (DPLL)
- Tries to build an assignment μ satisfying φ;
- At each step assigns a truth value to (all instances of) one atom.
- Performs deterministic choices first.

DPLL rules

$$\frac{\varphi_1 \wedge (l)}{\varphi_1[l|\top]}\ (Unit)$$

$$\frac{\varphi}{\varphi[l|\top]}\ (l\ Pure)$$

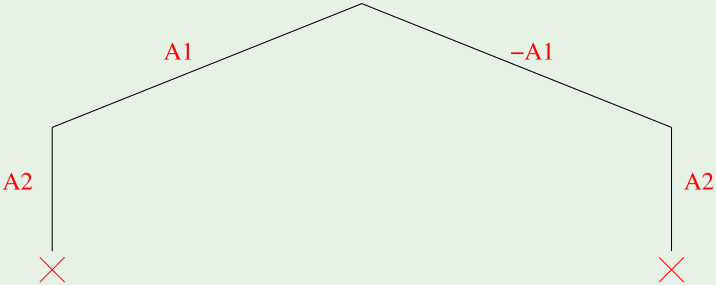
$$\frac{\varphi}{\varphi[l|\top] \quad \varphi[l|\bot]}\ (split)$$

(l is a pure literal in φ iff it occurs only positively).

- Split applied if and only if the others cannot be applied.
- Richer formalisms described in [40, 29, 30]

DPLL – example

$$\varphi = (A_1 \vee A_2) \wedge (A_1 \vee \neg A_2) \wedge (\neg A_1 \vee A_2) \wedge (\neg A_1 \vee \neg A_2)$$



DPLL Algorithm

function *DPLL*(φ, μ)

  if $\varphi = \top$ /* base */

    then return *True*;

  if $\varphi = \bot$ /* backtrack */

    then return *False*;

  if {a unit clause (l) occurs in φ} /* unit */

    then return *DPLL*(*assign*(l, φ), $\mu \wedge l$);

  if {a literal l occurs *pure* in φ} /* pure */

    then return *DPLL*(*assign*(l, φ), $\mu \wedge l$);

  l := *choose-literal*(φ); /* split */

  return *DPLL*(*assign*(l, φ), $\mu \wedge l$) **or**

    DPLL(*assign*($\neg l, \varphi$), $\mu \wedge \neg l$);

- The pure-literal rule is nowadays obsolete.
- *choose-literal*(φ) picks only variables still occurring in the formula

DPLL Algorithm

```
function DPLL(φ, μ)
    if φ = ⊤                                          /* base      */
        then return True;
    if φ = ⊥                                          /* backtrack */
        then return False;
    if {a unit clause (l) occurs in φ}                /* unit      */
        then return DPLL(assign(l, φ), μ ∧ l);
    if {a literal l occurs pure in φ}                 /* pure      */
        then return DPLL(assign(l, φ), μ ∧ l);
    l := choose-literal(φ);                           /* split     */
    return  DPLL(assign(l, φ), μ ∧ l)  or
            DPLL(assign(¬l, φ), μ ∧ ¬l);
```

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    then return *True*;
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    then return *False*;
  if {a unit clause (l) occurs in φ} /* unit */
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  if {a literal l occurs *pure* in φ} /* pure */
    then return *DPLL*(*assign*(l, φ), $\mu \wedge l$);
  l := choose-literal(φ); /* split */
  return *DPLL*(*assign*(l, φ), $\mu \wedge l$) **or**
    DPLL(*assign*($\neg l, \varphi$), $\mu \wedge \neg l$);

- The pure-literal rule is nowadays obsolete.
- *choose-literal*(φ) picks only variables still occurring in the formula

DPLL – example

DPLL (without pure-literal rule)

Here "choose-literal" selects variable in alphabetic, selecting true first.

$$
\begin{array}{l}
(\neg C) \wedge \\
(B \vee A \vee C) \wedge \\
(\neg A \vee D) \wedge \\
(\neg E \vee \neg A \vee F) \wedge \\
(\neg E \vee \neg F \vee \neg A) \wedge \\
(G \vee \neg A \vee E) \wedge \\
(E \vee \neg G \vee \neg A) \wedge \\
(A \vee H \vee C) \wedge \\
(\neg H \vee \neg I \vee A) \wedge \\
(I \vee L \vee M) \wedge \\
(\neg L \vee C \vee \neg M) \wedge \\
(A \vee \neg L \vee M) \wedge \\
(L \vee N \vee \neg H) \wedge \\
(I \vee L \vee \neg N)
\end{array}
$$

$\Longrightarrow$ UNSAT

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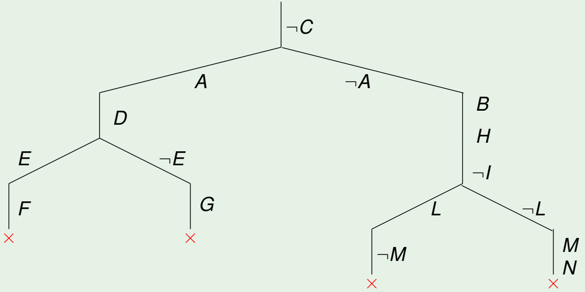
(E \vee \neg G \vee \neg A) \wedge \\
(A \vee H \vee C) \wedge \\
(\neg H \vee \neg I \vee A) \wedge \\
(I \vee L \vee M) \wedge \\
(\neg L \vee C \vee \neg M) \wedge \\
(A \vee \neg L \vee M) \wedge \\
(L \vee N \vee \neg H) \wedge \\
(I \vee L \vee \neg N)
\end{array}
$$



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(\neg E & \vee \neg F & \vee \neg A) & \wedge \\
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(E & \vee \neg G & \vee \neg A) & \wedge \\
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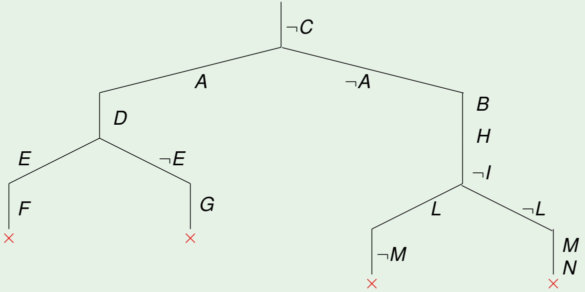
(\neg L & \vee C & \vee \neg M) & \wedge \\
(A & \vee \neg L & \vee M) & \wedge \\
(L & \vee N & \vee \neg H) & \wedge \\
(I & \vee L & \vee \neg N) &
\end{array}
$$



$\Longrightarrow$ UNSAT

DPLL – summary

- Handles CNF formulas (non-CNF variant known [1, 15]).
- Branches on truth values
  $\Longrightarrow$ all instances of an atom assigned simultaneously
- Postpones branching as much as possible.
- Mostly ignored by logicians.
- (The grandfather of) the most efficient SAT algorithms
  $\Longrightarrow$ loved by computer scientists.
- Requires polynomial space
- Choose_literal() critical!
- Many very efficient implementations [42, 38, 2, 28].

Outline

Stochastic Local Search SAT techniques: GSAT, WSAT [37, 36]

- Hill-Climbing techniques: GSAT, WSAT
- looks for a complete assignment;
- starts from a random assignment;
- Greedy search: looks for a better “neighbor” assignment
- Avoid local minima: restart & random walk

The GSAT algorithm [37]

function *GSAT*(φ)
    for $i := 1$ **to** Max-tries **do**
        μ := rand-assign(φ);
        for $j := 1$ **to** Max-flips **do**
            if ($score(\varphi, \mu) = 0$)
                then return True;
                else Best-flips := hill-climb(φ, μ);
                    A_i := rand-pick(Best-flips);
                    μ := flip(A_i, μ);
        end
    end
    return "no satisfying assignment found".

The WalkSAT algorithm(s) [36]

```
function WalkSAT(φ)
    for i := 1 to Max-tries do
        μ := rand-assign(φ);
        for j := 1 to Max-flips do
            if (score(φ, μ) = 0)
                then return True;
                else C := randomly-pick-clause(unsat-clauses(φ, μ));
                    A_i := heuristically-select-variable(C);
                    μ := flip(A_i, μ);
        end
    end
    return "no satisfying assignment found".
```

- many variants available [18, 41, 3]

SLS SAT solvers – summary

- Handle only CNF formulas.
- Incomplete
- Extremely efficient for some (satisfiable) problems.
- Require polynomial space
- Used in Artificial Intelligence (e.g., planning)
- Lots of variants (see e.g. [20])
- Non-CNF Variants: [34, 35, 4]

Outline

Ordered Binary Decision Diagrams (OBDDs) [8]]

Canonical representation of Boolean formulas

- "If-then-else" binary direct acyclic graphs (DAGs) with one root and two leaves: 1, 0 (or $\top$,$\bot$; or T, F)
- Variable ordering $A_1, A_2, ..., A_n$ imposed a priori.
- Paths leading to 1 represent models
  Paths leading to 0 represent counter-models

Note

Some authors call them Reduced Ordered Binary Decision Diagrams (ROBDDs)

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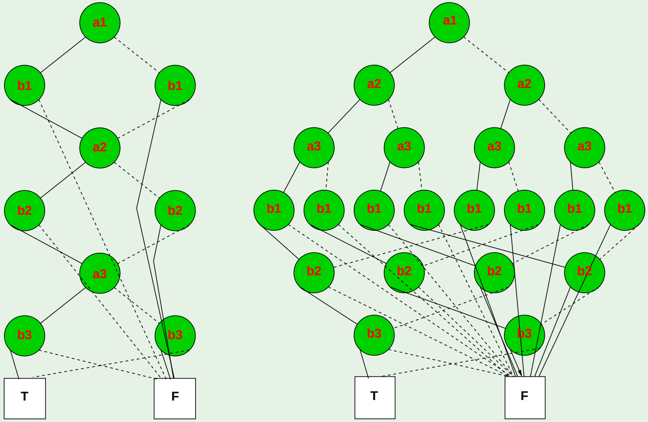
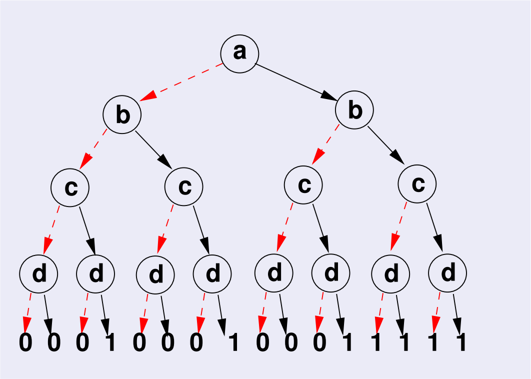
OBDD - Examples



OBDDs of $(a_1 \leftrightarrow b_1) \wedge (a_2 \leftrightarrow b_2) \wedge (a_3 \leftrightarrow b_3)$ with different variable orderings

Ordered Decision Trees

- Ordered Decision Tree: from root to leaves, variables are encountered always in the same order
- Example: Ordered Decision tree for $\varphi = (a \wedge b) \vee (c \wedge d)$



From Ordered Decision Trees to OBDD's: reductions

- Recursive applications of the following reductions:
  - share subnodes: point to the same occurrence of a subtree (via hash consing)
  - remove redundancies: nodes with same left and right children can be eliminated ("if A then B else B" $\Longrightarrow$ "B")

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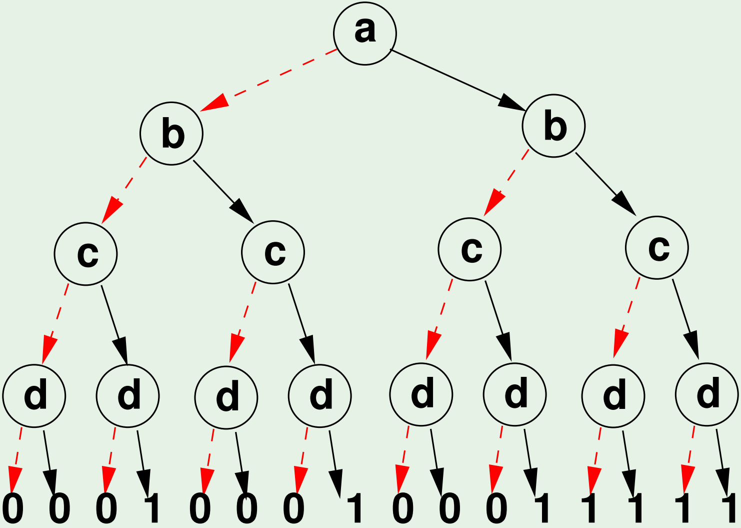
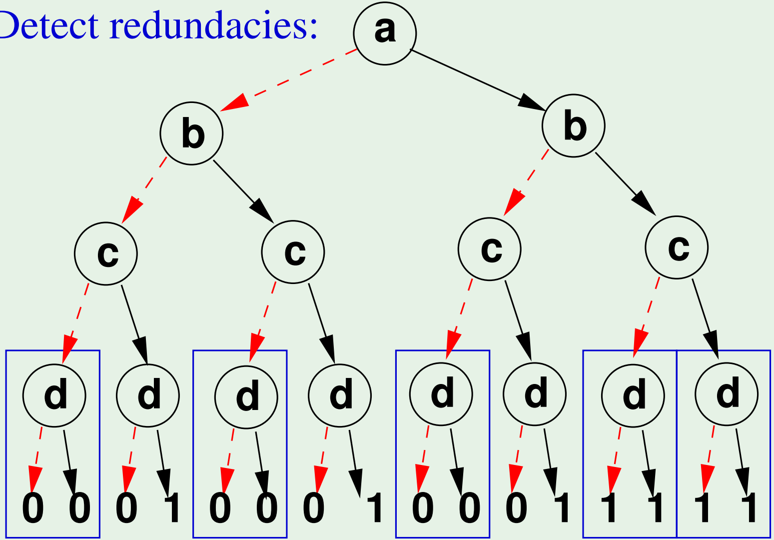
Reduction: example



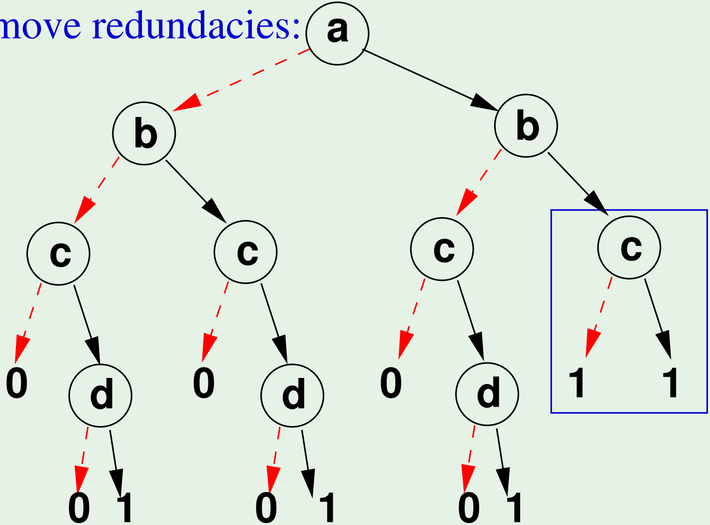
Reduction: example

Detect redundacies:



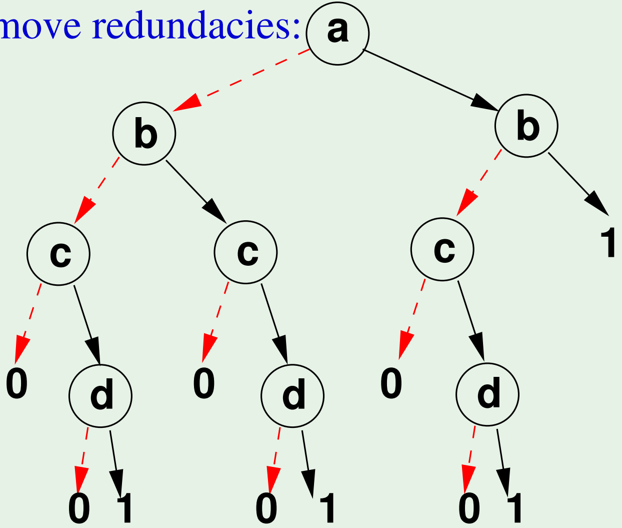
Reduction: example

Remove redundacies:



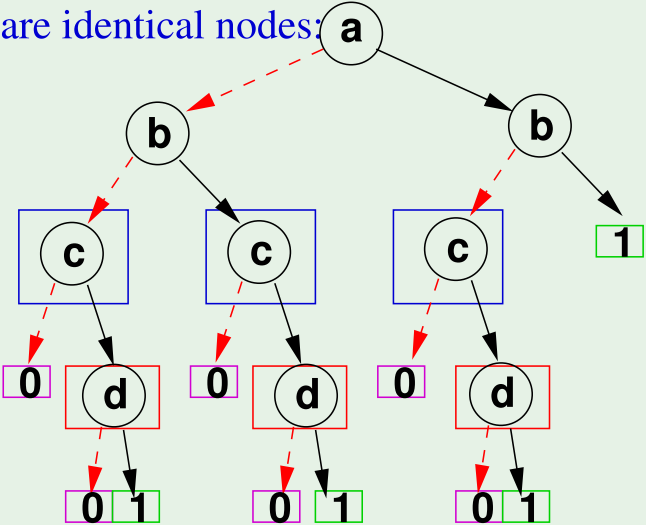
Reduction: example

Remove redundacies:



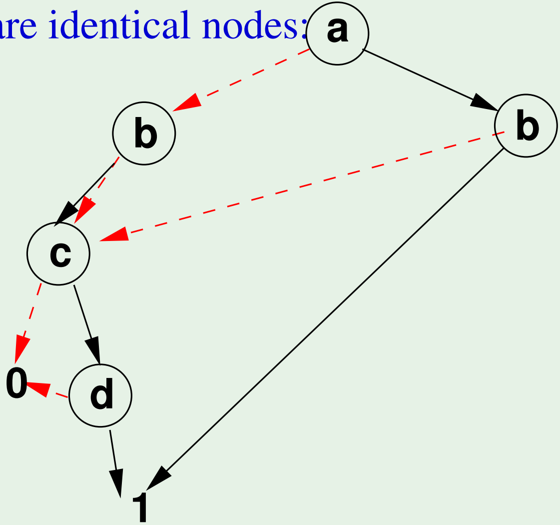
Reduction: example

Share identical nodes:



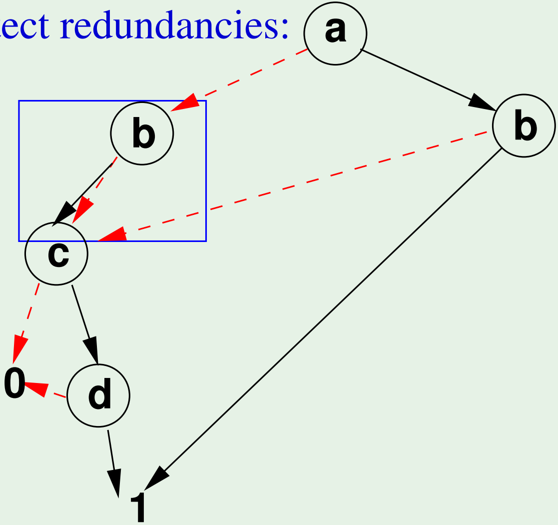
Reduction: example

Share identical nodes:



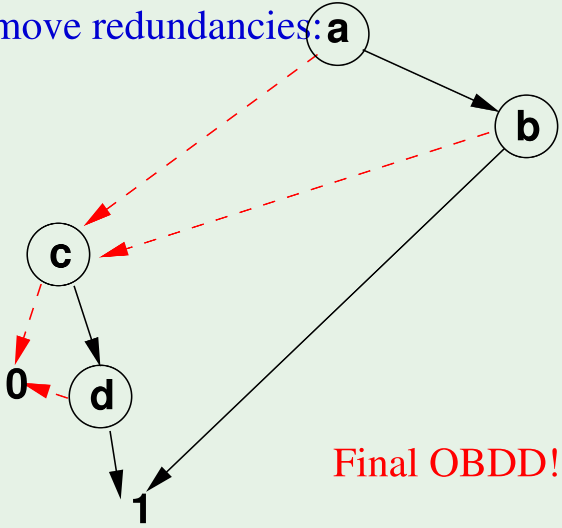
Reduction: example

Detect redundancies:



Reduction: example

Remove redundancies:



Final OBDD!

If-Then-Else Operators: "*ite*(...)"

If-Then-Else Operators: "*ite*(...)"

- $ite(\phi, \varphi^\top, \varphi^\bot)$: "If ϕ Then $\varphi^\top$ Else $\varphi^\bot$"
- $ite(\phi, \varphi^\top, \varphi^\bot) \stackrel{\text{def}}{=} ((\neg\phi \vee \varphi^\top) \wedge (\phi \vee \varphi^\bot) \Longleftrightarrow ((\phi \wedge \varphi^\top) \vee (\neg\phi \wedge \varphi^\bot))$
- properties:

$$
\begin{aligned}
\neg ite(\phi, \varphi^\top, \varphi^\bot) &= ite(\phi, \neg\varphi^\top, \neg\varphi^\bot)\\
ite(\phi, \varphi_1^\top, \varphi_1^\bot)\ op\ ite(\phi, \varphi_2^\top, \varphi_2^\bot) &= ite(\phi, (\varphi_1^\top\ op\ \varphi_2^\top), (\varphi_1^\bot\ op\ \varphi_2^\bot))\\
ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot) &= ite(\phi_1, (\varphi_1^\top\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot)),\\
&\qquad (\varphi_1^\bot\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot)))\\
&= ite(\phi_2, (ite(\phi_1, \varphi_1^\top, \varphi_1^\bot) op\ \varphi_2^\top),\\
&\qquad (ite(\phi_1, \varphi_1^\top, \varphi_1^\bot) op\ \varphi_2^\bot))
\end{aligned}
$$

$op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

If-Then-Else Operators: "*ite*(...)"

If-Then-Else Operators: "*ite*(...)"

- $ite(\phi, \varphi^{\top}, \varphi^{\bot})$: "If ϕ Then $\varphi^{\top}$ Else $\varphi^{\bot}$"
- $ite(\phi, \varphi^{\top}, \varphi^{\bot}) \stackrel{\text{def}}{=} ((\neg\phi \vee \varphi^{\top}) \wedge (\phi \vee \varphi^{\bot}) \iff ((\phi \wedge \varphi^{\top}) \vee (\neg\phi \wedge \varphi^{\bot}))$
- properties:

$$
\begin{aligned}
\neg ite(\phi, \varphi^{\top}, \varphi^{\bot}) &= ite(\phi, \neg\varphi^{\top}, \neg\varphi^{\bot}) \\
ite(\phi, \varphi_1^{\top}, \varphi_1^{\bot}) \ op\ ite(\phi, \varphi_2^{\top}, \varphi_2^{\bot}) &= ite(\phi, (\varphi_1^{\top}\ op\ \varphi_2^{\top}), (\varphi_1^{\bot}\ op\ \varphi_2^{\bot})) \\
ite(\phi_1, \varphi_1^{\top}, \varphi_1^{\bot}) \ op\ ite(\phi_2, \varphi_2^{\top}, \varphi_2^{\bot}) &= ite(\phi_1, (\varphi_1^{\top}\ op\ ite(\phi_2, \varphi_2^{\top}, \varphi_2^{\bot})), \\
&\qquad (\varphi_1^{\bot}\ op\ ite(\phi_2, \varphi_2^{\top}, \varphi_2^{\bot}))) \\
&= ite(\phi_2, (ite(\phi_1, \varphi_1^{\top}, \varphi_1^{\bot})\ op\ \varphi_2^{\top}), \\
&\qquad (ite(\phi_1, \varphi_1^{\top}, \varphi_1^{\bot})\ op\ \varphi_2^{\bot}))
\end{aligned}
$$

$op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

If-Then-Else Operators: "*ite*(...)"

- $ite(\phi, \varphi^\top, \varphi^\bot)$: "If ϕ Then $\varphi^\top$ Else $\varphi^\bot$"
- $ite(\phi, \varphi^\top, \varphi^\bot) \stackrel{\text{def}}{=} ((\neg\phi \vee \varphi^\top) \wedge (\phi \vee \varphi^\bot) \Longleftrightarrow ((\phi \wedge \varphi^\top) \vee (\neg\phi \wedge \varphi^\bot))$
- properties:

$$\begin{aligned}
\neg ite(\phi, \varphi^\top, \varphi^\bot) &= ite(\phi, \neg\varphi^\top, \neg\varphi^\bot) \\
ite(\phi, \varphi_1^\top, \varphi_1^\bot)\ op\ ite(\phi, \varphi_2^\top, \varphi_2^\bot) &= ite(\phi, (\varphi_1^\top\ op\ \varphi_2^\top), (\varphi_1^\bot\ op\ \varphi_2^\bot)) \\
ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot) &= ite(\phi_1, (\varphi_1^\top\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot)), \\
&\qquad (\varphi_1^\bot\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot))) \\
&= ite(\phi_2, (ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ \varphi_2^\top), \\
&\qquad (ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ \varphi_2^\bot))
\end{aligned}$$

$op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

If-Then-Else Operators: "*ite*(...)"

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- $ite(\phi, \varphi^{\top}, \varphi^{\bot})$: "If ϕ Then $\varphi^{\top}$ Else $\varphi^{\bot}$"
- $ite(\phi, \varphi^{\top}, \varphi^{\bot}) \stackrel{\text{def}}{=} ((\neg\phi \vee \varphi^{\top}) \wedge (\phi \vee \varphi^{\bot}) \iff ((\phi \wedge \varphi^{\top}) \vee (\neg\phi \wedge \varphi^{\bot}))$
- properties:

$$\neg ite(\phi, \varphi^{\top}, \varphi^{\bot}) = ite(\phi, \neg\varphi^{\top}, \neg\varphi^{\bot})$$

$$ite(\phi, \varphi_1^{\top}, \varphi_1^{\bot}) \; op \; ite(\phi, \varphi_2^{\top}, \varphi_2^{\bot}) = ite(\phi, (\varphi_1^{\top} \; op \; \varphi_2^{\top}), (\varphi_1^{\bot} \; op \; \varphi_2^{\bot}))$$

$$\begin{aligned} ite(\phi_1, \varphi_1^{\top}, \varphi_1^{\bot}) \; op \; ite(\phi_2, \varphi_2^{\top}, \varphi_2^{\bot}) &= ite(\phi_1, (\varphi_1^{\top} \; op \; ite(\phi_2, \varphi_2^{\top}, \varphi_2^{\bot})), \\ &\qquad (\varphi_1^{\bot} \; op \; ite(\phi_2, \varphi_2^{\top}, \varphi_2^{\bot}))) \\ &= ite(\phi_2, (ite(\phi_1, \varphi_1^{\top}, \varphi_1^{\bot}) \; op \; \varphi_2^{\top}), \\ &\qquad (ite(\phi_1, \varphi_1^{\top}, \varphi_1^{\bot}) \; op \; \varphi_2^{\bot})) \end{aligned}$$

$op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

If-Then-Else Operators: "*ite*(...)"

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- $ite(\phi, \varphi^{\top}, \varphi^{\bot})$: "If ϕ Then $\varphi^{\top}$ Else $\varphi^{\bot}$"
- $ite(\phi, \varphi^{\top}, \varphi^{\bot}) \stackrel{\text{def}}{=} ((\neg\phi \vee \varphi^{\top}) \wedge (\phi \vee \varphi^{\bot}) \Longleftrightarrow ((\phi \wedge \varphi^{\top}) \vee (\neg\phi \wedge \varphi^{\bot}))$
- properties:

$$
\begin{aligned}
\neg ite(\phi, \varphi^{\top}, \varphi^{\bot}) &= ite(\phi, \neg\varphi^{\top}, \neg\varphi^{\bot}) \\
ite(\phi, \varphi_1^{\top}, \varphi_1^{\bot}) \ op\ ite(\phi, \varphi_2^{\top}, \varphi_2^{\bot}) &= ite(\phi, (\varphi_1^{\top}\ op\ \varphi_2^{\top}), (\varphi_1^{\bot}\ op\ \varphi_2^{\bot})) \\
ite(\phi_1, \varphi_1^{\top}, \varphi_1^{\bot}) \ op\ ite(\phi_2, \varphi_2^{\top}, \varphi_2^{\bot}) &= ite(\phi_1, (\varphi_1^{\top}\ op\ ite(\phi_2, \varphi_2^{\top}, \varphi_2^{\bot})), \\
&\qquad (\varphi_1^{\bot}\ op\ ite(\phi_2, \varphi_2^{\top}, \varphi_2^{\bot}))) \\
&= ite(\phi_2, (ite(\phi_1, \varphi_1^{\top}, \varphi_1^{\bot})\ op\ \varphi_2^{\top}), \\
&\qquad (ite(\phi_1, \varphi_1^{\top}, \varphi_1^{\bot})\ op\ \varphi_2^{\bot}))
\end{aligned}
$$

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- properties:

$$
\begin{aligned}
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ite(\phi, \varphi_1^\top, \varphi_1^\bot)\ op\ ite(\phi, \varphi_2^\top, \varphi_2^\bot) &= ite(\phi, (\varphi_1^\top\ op\ \varphi_2^\top), (\varphi_1^\bot\ op\ \varphi_2^\bot)) \\
ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot) &= ite(\phi_1, (\varphi_1^\top\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot)), \\
&\qquad (\varphi_1^\bot\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot))) \\
&= ite(\phi_2, (ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ \varphi_2^\top), \\
&\qquad (ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ \varphi_2^\bot))
\end{aligned}
$$

$op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

If-Then-Else Operators: “*ite*(...)”

If-Then-Else Operators: “*ite*(...)”

- $ite(\phi, \varphi^\top, \varphi^\bot)$: “If ϕ Then $\varphi^\top$ Else $\varphi^\bot$”
- $ite(\phi, \varphi^\top, \varphi^\bot) \stackrel{\text{def}}{=} ((\neg\phi \vee \varphi^\top) \wedge (\phi \vee \varphi^\bot) \iff ((\phi \wedge \varphi^\top) \vee (\neg\phi \wedge \varphi^\bot))$
- properties:

$$
\begin{aligned}
\neg ite(\phi, \varphi^\top, \varphi^\bot) &= ite(\phi, \neg\varphi^\top, \neg\varphi^\bot) \\
ite(\phi, \varphi_1^\top, \varphi_1^\bot)\ op\ ite(\phi, \varphi_2^\top, \varphi_2^\bot) &= ite(\phi, (\varphi_1^\top\ op\ \varphi_2^\top), (\varphi_1^\bot\ op\ \varphi_2^\bot)) \\
ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot) &= ite(\phi_1, (\varphi_1^\top\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot)), \\
&\qquad (\varphi_1^\bot\ op\ ite(\phi_2, \varphi_2^\top, \varphi_2^\bot))) \\
&= ite(\phi_2, (ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ \varphi_2^\top), \\
&\qquad (ite(\phi_1, \varphi_1^\top, \varphi_1^\bot)\ op\ \varphi_2^\bot))
\end{aligned}
$$

$op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

Recursive structure of an OBDD

Assume the variable ordering $A_1, A_2, ..., A_n$:

$$
\begin{array}{rcl}
OBDD(\top, \{A_1, A_2, ..., A_n\}) & = & 1 \\
OBDD(\bot, \{A_1, A_2, ..., A_n\}) & = & 0 \\
OBDD(\varphi, \{A_1, A_2, ..., A_n\}) & = & \textit{if } A_1 \\
 & & \textit{then } OBDD(\varphi[A_1|\top], \{A_2, ..., A_n\}) \\
 & & \textit{else } OBDD(\varphi[A_1|\bot], \{A_2, ..., A_n\})
\end{array}
$$

Incrementally building an OBDD

- $obdd\_build(\top, \{...\}) := \top$,
- $obdd\_build(\bot, \{...\}) := \bot$,
- $obdd\_build(A_i, \{...\}) := ite(A_i, \top, \bot)$,
- $obdd\_build((\neg\varphi), \{A_1, ..., A_n\}) :=$
  $apply(\neg, obdd\_build(\varphi, \{A_1, ..., A_n\}))$
- $obdd\_build((\varphi_1 \ op\ \varphi_2), \{A_1, ..., A_n\}) :=$
  $reduce($
  $apply(\quad op,$
  $obdd\_build(\varphi_1, \{A_1, ..., A_n\}),$
  $obdd\_build(\varphi_2, \{A_1, ..., A_n\})$
  $))$
  $op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

Incrementally building an OBDD

- $obdd\_build(\top, \{...\}) := \top$,
- $obdd\_build(\bot, \{...\}) := \bot$,
- $obdd\_build(A_i, \{...\}) := ite(A_i, \top, \bot)$,
- $obdd\_build((\neg\varphi), \{A_1, ..., A_n\}) :=$
  $apply(\neg, obdd\_build(\varphi, \{A_1, ..., A_n\}))$
- $obdd\_build((\varphi_1 \; op \; \varphi_2), \{A_1, ..., A_n\}) :=$
  $reduce($
  $apply(\quad op,$
  $obdd\_build(\varphi_1, \{A_1, ..., A_n\}),$
  $obdd\_build(\varphi_2, \{A_1, ..., A_n\})$
  $))$
  $op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

Incrementally building an OBDD

- $obdd\_build(\top, \{...\}) := \top$,
- $obdd\_build(\bot, \{...\}) := \bot$,
- $obdd\_build(A_i, \{...\}) := ite(A_i, \top, \bot)$,
- $obdd\_build((\neg\varphi), \{A_1, ..., A_n\}) :=$
  $apply(\neg, obdd\_build(\varphi, \{A_1, ..., A_n\}))$
- $obdd\_build((\varphi_1 \; op \; \varphi_2), \{A_1, ..., A_n\}) :=$
  $reduce($
  $apply(\quad op,$
  $obdd\_build(\varphi_1, \{A_1, ..., A_n\}),$
  $obdd\_build(\varphi_2, \{A_1, ..., A_n\})$
  $))$
  $op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

Incrementally building an OBDD

- $obdd\_build(\top, \{...\}) := \top$,
- $obdd\_build(\bot, \{...\}) := \bot$,
- $obdd\_build(A_i, \{...\}) := ite(A_i, \top, \bot)$,
- $obdd\_build((\neg\varphi), \{A_1, ..., A_n\}) :=$
  $apply(\neg, obdd\_build(\varphi, \{A_1, ..., A_n\}))$
- $obdd\_build((\varphi_1 \ op\ \varphi_2), \{A_1, ..., A_n\}) :=$
  $reduce($
  $apply(\quad op,$
  $obdd\_build(\varphi_1, \{A_1, ..., A_n\}),$
  $obdd\_build(\varphi_2, \{A_1, ..., A_n\})$
  $))$
  $op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

Incrementally building an OBDD

- $\mathit{obdd\_build}(\top, \{...\}) := \top$,
- $\mathit{obdd\_build}(\bot, \{...\}) := \bot$,
- $\mathit{obdd\_build}(A_i, \{...\}) := \mathit{ite}(A_i, \top, \bot)$,
- $\mathit{obdd\_build}((\neg\varphi), \{A_1, ..., A_n\}) :=$
  $\mathit{apply}(\neg, \mathit{obdd\_build}(\varphi, \{A_1, ..., A_n\}))$
- $\mathit{obdd\_build}((\varphi_1 \ \mathit{op} \ \varphi_2), \{A_1, ..., A_n\}) :=$

$$
\begin{array}{l}
\mathit{reduce}(\\
\quad \mathit{apply}(\quad \mathit{op}, \\
\qquad\qquad\quad \mathit{obdd\_build}(\varphi_1, \{A_1, ..., A_n\}), \\
\qquad\qquad\quad \mathit{obdd\_build}(\varphi_2, \{A_1, ..., A_n\}) \\
))
\end{array}
$$

$\mathit{op} \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

Incrementally building an OBDD (cont.)

- $apply\ (op,\ O_i, O_j) := (O_i\ op\ O_j)$ **if** $(O_i \in \{\top, \bot\}$ or $O_j \in \{\top, \bot\})$
- $apply\ (\neg,\ ite(A_i, \varphi_i^\top, \varphi_i^\bot)) :=$
  $ite(A_i, apply(\neg, \varphi_i^\top), apply(\neg, \varphi_i^\bot))$
- $apply\ (op,\ ite(A_i, \varphi_i^\top, \varphi_i^\bot),\ ite(A_j, \varphi_j^\top, \varphi_j^\bot)) :=$
  if $(A_i = A_j)$ **then** $ite(A_i,\ apply\ (op, \varphi_i^\top, \varphi_j^\top),\ apply\ (op, \varphi_i^\bot, \varphi_j^\bot))$
  if $(A_i < A_j)$ **then** $ite(A_i,\ apply\ (op, \varphi_i^\top, ite(A_j, \varphi_j^\top, \varphi_j^\bot)),\ apply\ (op, \varphi_i^\bot, ite(A_j, \varphi_j^\top, \varphi_j^\bot)))$
  if $(A_i > A_j)$ **then** $ite(A_j,\ apply\ (op, ite(A_i, \varphi_i^\top, \varphi_i^\bot), \varphi_j^\top),\ apply\ (op, ite(A_i, \varphi_i^\top, \varphi_i^\bot), \varphi_j^\bot))$

$op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

Incrementally building an OBDD (cont.)

- $apply\ (op,\ O_i, O_j) := (O_i\ op\ O_j)$ **if** $(O_i \in \{\top, \bot\}$ or $O_j \in \{\top, \bot\})$
- $apply\ (\neg,\ ite(A_i, \varphi_i^\top, \varphi_i^\bot)) :=$
  $ite(A_i, apply(\neg, \varphi_i^\top), apply(\neg, \varphi_i^\bot))$
- $apply\ (op,\ ite(A_i, \varphi_i^\top, \varphi_i^\bot),\ ite(A_j, \varphi_j^\top, \varphi_j^\bot)) :=$
  if $(A_i = A_j)$ **then** $ite(A_i,\ apply\ (op, \varphi_i^\top, \varphi_j^\top),\ apply\ (op, \varphi_i^\bot, \varphi_j^\bot))$
  if $(A_i < A_j)$ **then** $ite(A_i,\ apply\ (op, \varphi_i^\top, ite(A_j, \varphi_j^\top, \varphi_j^\bot)),\ apply\ (op, \varphi_i^\bot, ite(A_j, \varphi_j^\top, \varphi_j^\bot)))$
  if $(A_i > A_j)$ **then** $ite(A_j,\ apply\ (op, ite(A_i, \varphi_i^\top, \varphi_i^\bot), \varphi_j^\top),\ apply\ (op, ite(A_i, \varphi_i^\top, \varphi_i^\bot), \varphi_j^\bot))$

$op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

Incrementally building an OBDD (cont.)

- $apply\ (op,\ O_i, O_j) := (O_i\ op\ O_j)$ **if** $(O_i \in \{\top, \bot\}$ or $O_j \in \{\top, \bot\})$
- $apply\ (\neg,\ ite(A_i, \varphi_i^\top, \varphi_i^\bot)) :=$
  $ite(A_i, apply(\neg, \varphi_i^\top), apply(\neg, \varphi_i^\bot))$
- $apply\ (op,\ ite(A_i, \varphi_i^\top, \varphi_i^\bot),\ ite(A_j, \varphi_j^\top, \varphi_j^\bot)) :=$
  if $(A_i = A_j)$ **then** $ite(A_i,\ apply\ (op, \varphi_i^\top, \varphi_j^\top),$
  $apply\ (op, \varphi_i^\bot, \varphi_j^\bot))$
  if $(A_i < A_j)$ **then** $ite(A_i,\ apply\ (op, \varphi_i^\top, ite(A_j, \varphi_j^\top, \varphi_j^\bot)),$
  $apply\ (op, \varphi_i^\bot, ite(A_j, \varphi_j^\top, \varphi_j^\bot)))$
  if $(A_i > A_j)$ **then** $ite(A_j,\ apply\ (op, ite(A_i, \varphi_i^\top, \varphi_i^\bot), \varphi_j^\top),$
  $apply\ (op, ite(A_i, \varphi_i^\top, \varphi_i^\bot), \varphi_j^\bot))$

$op \in \{\wedge, \vee, \rightarrow, \leftarrow, \leftrightarrow, \oplus\}$

Incrementally building an OBDD (cont.)

- Ex: build the obdd for $A_1 \vee A_2$ from those of A_1, A_2 (order: A_1, A_2):

$$
\begin{array}{ll}
& apply(\vee, \overbrace{ite(A_1, \top, \bot)}^{A_1}, \overbrace{ite(A_2, \top, \bot)}^{A_2}) \\
= & ite(A_1,\ apply(\vee, \top, ite(A_1, \top, \bot)),\ apply(\vee, \bot, ite(A_2, \top, \bot))\ ) \\
= & ite(A_1,\ \top,\ ite(A_2, \top, \bot)\ )
\end{array}
$$

- Ex: build the obdd for $(A_1 \vee A_2) \wedge (A_1 \vee \neg A_2)$ from those of $(A_1 \vee A_2)$, $(A_1 \vee \neg A_2)$ (order: A_1, A_2):

$$
\begin{array}{ll}
& apply(\wedge,\ \overbrace{ite(A_1, \top, ite(A_2, \top, \bot))}^{(A_1 \vee A_2)},\ \overbrace{ite(A_1, \top, ite(A_2, \bot, \top))}^{(A_1 \vee \neg A_2)}, \\
= & ite(A_1,\ apply(\wedge, \top, \top),\ apply(\wedge,\ ite(A_2, \top, \bot),\ ite(A_2, \bot, \top)) \\
= & ite(A_1,\ \top,\ ite(A_2,\ apply(\wedge, \top, \bot),\ apply(\wedge, \bot, \top))) \\
= & ite(A_1,\ \top,\ ite(A_2,\ \bot,\ \bot)) \\
= & ite(A_1,\ \top,\ \bot)
\end{array}
$$

Incrementally building an OBDD (cont.)

- Ex: build the obdd for $A_1 \vee A_2$ from those of A_1, A_2 (order: A_1, A_2):

$$
\begin{aligned}
& apply(\vee, \overbrace{ite(A_1, \top, \bot)}^{A_1}, \overbrace{ite(A_2, \top, \bot)}^{A_2}) \\
= \;& ite(A_1,\; apply(\vee, \top, ite(A_1, \top, \bot)),\; apply(\vee, \bot, ite(A_2, \top, \bot))\;) \\
= \;& ite(A_1,\; \top,\; ite(A_2, \top, \bot)\;)
\end{aligned}
$$

- Ex: build the obdd for $(A_1 \vee A_2) \wedge (A_1 \vee \neg A_2)$ from those of $(A_1 \vee A_2)$, $(A_1 \vee \neg A_2)$ (order: A_1, A_2):

$$
\begin{aligned}
& apply(\wedge,\; \overbrace{ite(A_1, \top, ite(A_2, \top, \bot))}^{(A_1 \vee A_2)},\; \overbrace{ite(A_1, \top, ite(A_2, \bot, \top))}^{(A_1 \vee \neg A_2)}), \\
= \;& ite(A_1,\; apply(\wedge, \top, \top),\; apply(\wedge,\; ite(A_2, \top, \bot),\; ite(A_2, \bot, \top)) \\
= \;& ite(A_1,\; \top,\; ite(A_2,\; apply(\wedge, \top, \bot),\; apply(\wedge, \bot, \top))) \\
= \;& ite(A_1,\; \top,\; ite(A_2,\; \bot,\; \bot)) \\
= \;& ite(A_1,\; \top,\; \bot)
\end{aligned}
$$

OBBD incremental building – example

$$\varphi = (A_1 \vee A_2) \wedge (A_1 \vee \neg A_2) \wedge (\neg A_1 \vee A_2) \wedge (\neg A_1 \vee \neg A_2)$$

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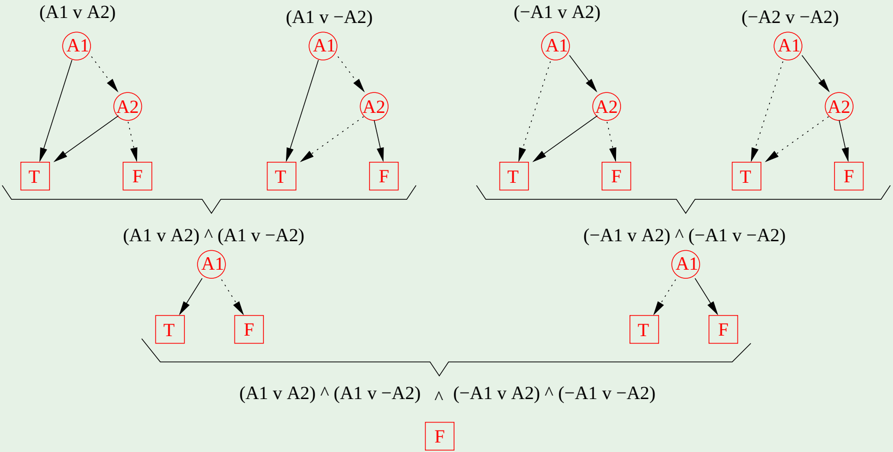

Critical choice of variable Orderings in OBDD's

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Linear size

Exponential size

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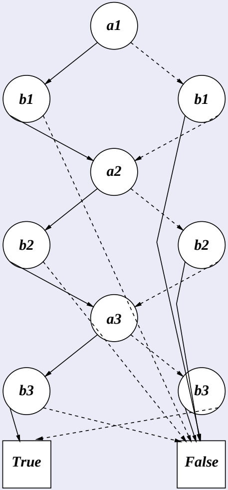

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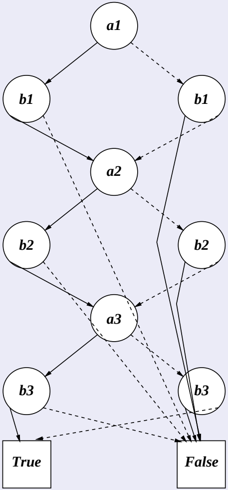

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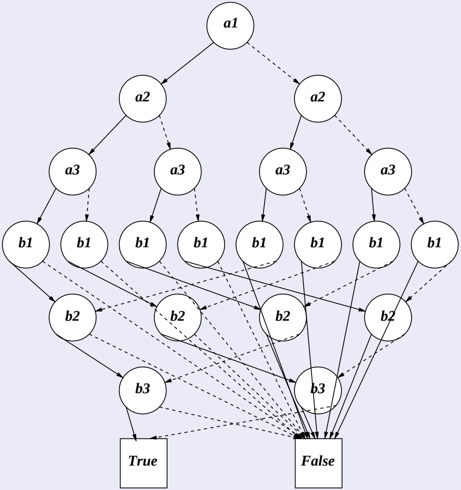

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OBDD's as canonical representation of Boolean formulas

- An OBDD is a canonical representation of a Boolean formula: once the variable ordering is established, equivalent formulas are represented by the same OBDD:

$$\varphi_1 \leftrightarrow \varphi_2 \iff OBDD(\varphi_1) = OBDD(\varphi_2)$$

- equivalence check requires constant time!
  $\Longrightarrow$validity check requires constant time! ($\varphi \leftrightarrow \top$)
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- The size of OBDD's may grow exponentially wrt. the number of variables in worst-case
- Consequence of the canonicity of OBDD's (unless P = co-NP)
- Example: there exist no polynomial-size OBDD representing the electronic circuit of a bitwise multiplier

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- the equivalence check between two OBDDs is simple
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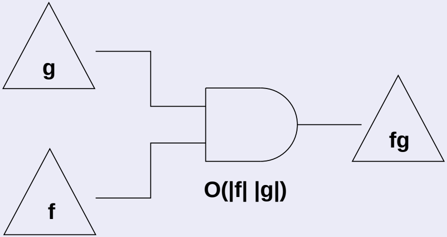

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Boolean quantification

Shannon's expansion:

- If v is a Boolean variable and f is a Boolean formula, then

$$\begin{aligned} \exists v.f &:= f|_{v=0} \vee f|_{v=1} \\ \forall v.f &:= f|_{v=0} \wedge f|_{v=1} \end{aligned}$$

- v does no more occur in $\exists v.f$ and $\forall v.f$!!
- Multi-variable quantification: $\exists (w_1, \ldots, w_n).f \ := \ \exists w_1 \ldots \exists w_n.f$

- Intuition:
  - $\mu \models \exists v.f$ iff exists $tvalue \in \{\top, \bot\}$ s.t. $\mu \cup \{v := tvalue\} \models f$
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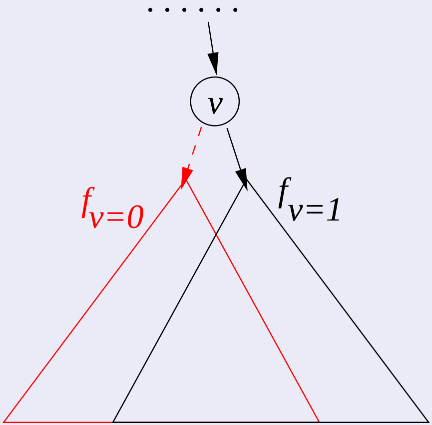
OBDD's and Boolean quantification

- OBDD's handle quantification operations quite efficiently
  - if f is a sub-OBDD labeled by variable v, then $f|_{v=1}$ and $f|_{v=0}$ are the "then" and "else" branches of f



$\Longrightarrow$ lots of sharing of subformulae!

Example

Let $\varphi \stackrel{\text{def}}{=} (A \wedge (B \vee C))$ and $\varphi' \stackrel{\text{def}}{=} \exists A.\forall B.\varphi$. Using the variable ordering "A, B, C", draw the OBDD corresponding to the formulas φ and φ'.

Example

Let $\varphi \stackrel{\text{def}}{=} (A \land (B \lor C))$ and $\varphi' \stackrel{\text{def}}{=} \exists A.\forall B.\varphi$. Using the variable ordering "A, B, C", draw the OBDD corresponding to the formulas φ and φ'.

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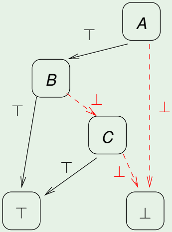

Example (cont.)

$\varphi' \stackrel{\text{def}}{=} \exists A.\forall B.(A \wedge (B \vee C))$

which corresponds to the following OBDD:

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$$
\begin{array}{lllll}
\varphi' \stackrel{\text{def}}{=} & \exists A.\forall B.\varphi & & & \\
= & \forall B.(A \wedge (B \vee C)))[A := \top] & & \vee & (\forall B.(A \wedge (B \vee C)))[A := \bot] \\
= & \forall B.(B \vee C)) & & \vee & \forall B.\bot \\
= & ((B \vee C)[B := \top] & \wedge \quad (B \vee C)[B := \bot]) & \vee & \bot \\
= & (\top & \wedge \quad C) & & \\
= & C & & &
\end{array}
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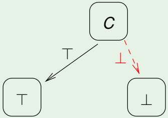

OBDD – summary

- Factorize common parts of the search tree (DAG)
- Require setting a variable ordering a priori (critical!)
- Canonical representation of a Boolean formula.
- Once built, logical operations (satisfiability, validity, equivalence) immediate.
- Represents all models and counter-models of the formula.
- Require exponential space in worst-case
- Very efficient for some practical problems (circuits, symbolic model checking).

Outline

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DPLL: “Classic” chronological backtracking

DPLL implements “classic” chronological backtracking:

- variable assignments (literals) stored in a stack
- each variable assignments labeled as “unit”, “open”, “closed”
- when a conflict is encountered, the stack is popped up to the most recent open assignment l
- l is toggled, is labeled as “closed”, and the search proceeds.

DPLL Chronological Backtracking: Drawbacks

Chronological backtracking always backtracks to the most recent branching point, even though a higher backtrack could be possible
$\Longrightarrow$ lots of useless search!

DPLL Chronological Backtracking: Example

$c_1 : \neg A_1 \vee A_2$
$c_2 : \neg A_1 \vee A_3 \vee A_9$
$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$
$c_4 : \neg A_4 \vee A_5 \vee A_{10}$
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$\ldots$

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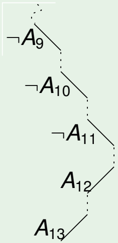

$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ...\}$
(initial assignment)

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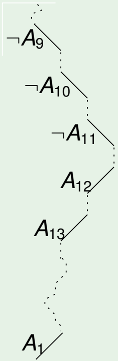

$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ..., A_1\}$
... (branch on A_1)

DPLL Chronological Backtracking: Example

$c_1 : \neg A_1 \vee A_2$ √

$c_2 : \neg A_1 \vee A_3 \vee A_9$ √

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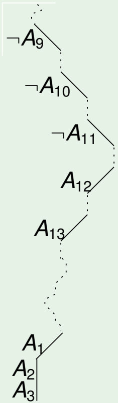

$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ..., A_1, A_2, A_3\}$
(unit A_2, A_3)

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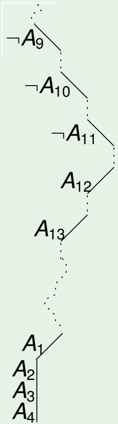

$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ..., A_1, A_2, A_3, A_4\}$
(unit A_4)

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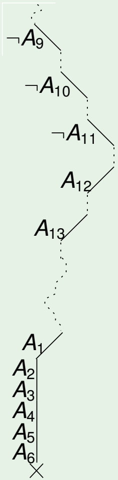

$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ..., A_1, A_2, A_3, A_4, A_5, A_6\}$

(unit A_5, A_6) $\Longrightarrow$ conflict

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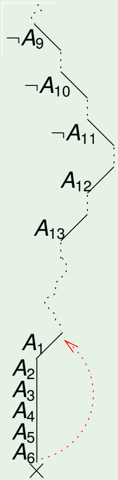

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$\Longrightarrow$ backtrack up to A_1

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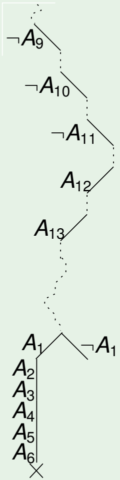

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(unit $\neg A_1$)

DPLL Chronological Backtracking: Example

$c_1 : \neg A_1 \vee A_2$ ✓

$c_2 : \neg A_1 \vee A_3 \vee A_9$ ✓

$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$

$c_4 : \neg A_4 \vee A_5 \vee A_{10}$

$c_5 : \neg A_4 \vee A_6 \vee A_{11}$

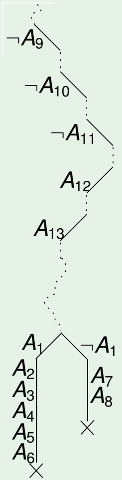
$c_6 : \neg A_5 \vee \neg A_6$

$c_7 : A_1 \vee A_7 \vee \neg A_{12}$ ✓

$c_8 : A_1 \vee A_8$ ✓

$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$ ×

...



$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ..., \neg A_1, A_7, A_8\}$

(unit A_7, A_8) $\Longrightarrow$ conflict

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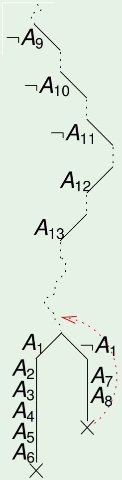

$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ...\}$
$\Longrightarrow$ backtrack to the most recent open branching point

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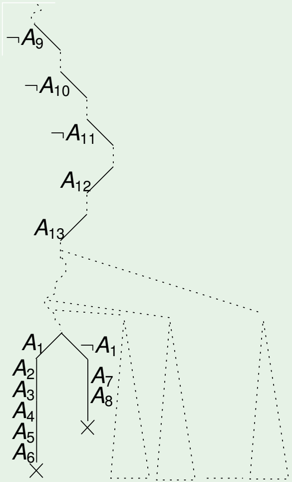

$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ...\}$
$\Longrightarrow$ lots of useless search before backtracking up to A_{13}!

Outline

Modern Conflict-Driven Clause-Learning SAT Solvers

- Non-recursive, stack-based implementations
- Based on Conflict-Driven Clause-Learning (CDCL) schema
  - inspired to conflict-driven backjumping and learning in CSPs
  - learns implied clauses as nogoods
- Random restarts
  - abandon the current search tree and restart on top level
  - previously-learned clauses maintained
- Smart literal selection heuristics (ex: VSIDS)
  - "static": scores updated only at the end of a branch
  - "local": privileges variable in recently learned clauses
- Smart preprocessing/inprocessing technique to simplify formulas
- Smart indexing techniques (e.g. 2-watched literals)
  - efficiently do/undo assignments and reveal unit clauses
- Allow Incremental Calls (stack-based interface)
  - allow for reusing previous search on "similar" problems

Can handle industrial problems with $10^6 - 10^7$ variables and clauses!

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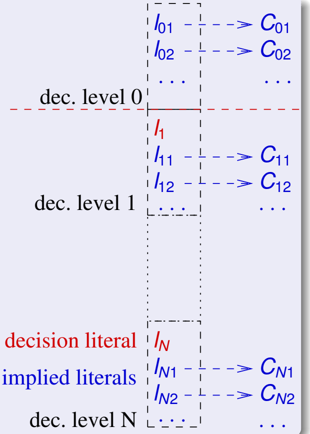
Stack-based representation of a truth assignment μ

- assign one truth-value at a time (add one literal to a stack representing μ)
- stack partitioned into decision levels:
  - one decision literal
  - its implied literals
  - each implied literal tagged with the clause causing its unit-propagation (antecedent clause)
- equivalent to an implication graph



Implication graph

- An implication graph is a DAG s.t.:
  - each node represents a variable assignment (literal)
  - each edge $l_i \xrightarrow{c} l$ is labeled with a clause
  - the node of a decision literal has no incoming edges
  - all edges incoming into a node l are labeled with the same clause c, s.t. $l_1 \xrightarrow{c} l, ..., l_n \xrightarrow{c} l$ iff $c = \neg l_1 \vee ... \vee \neg l_n \vee l$
    (c is said to be the antecedent clause of l)
  - when both l and $\neg l$ occur in the graph, we have a conflict.
- Intuition:
  - representation of the dependencies between literals in μ
  - the graph contains $l_1 \xrightarrow{c} l, ..., l_n \xrightarrow{c} l$ iff l has been obtained from $l_1, ..., l_n$ by unit propagation on c
  - a partition of the graph with all decision literals on one side and the conflict on the other represents a conflict set

Example

$c_1 : \neg A_1 \vee A_2$
$c_2 : \neg A_1 \vee A_3 \vee A_9$
$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$
$c_4 : \neg A_4 \vee A_5 \vee A_{10}$
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$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$
$\ldots$

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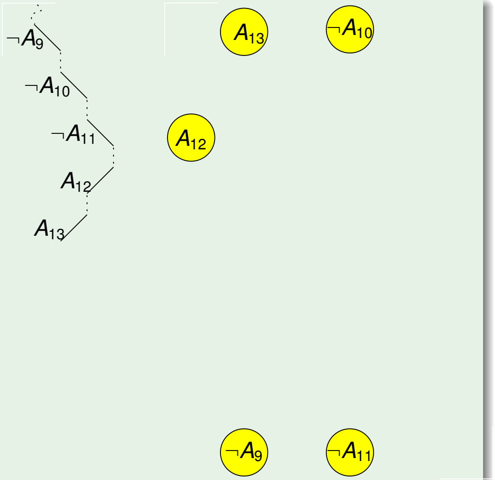

$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ...\}$
(Initial assignment. Note: c_1, ..., c_9 inconsistent.)

Example

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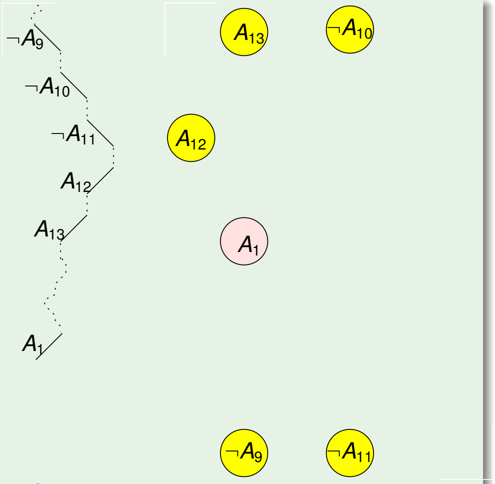
$c_6 : \neg A_5 \vee \neg A_6$
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$ √
$c_8 : A_1 \vee A_8$ √
$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$
...



$\{\ldots, \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, \ldots, A_1\}$
... (decide A_1)

Example

$c_1 : \neg A_1 \lor A_2$ √
$c_2 : \neg A_1 \lor A_3 \lor A_9$ √
$c_3 : \neg A_2 \lor \neg A_3 \lor A_4$
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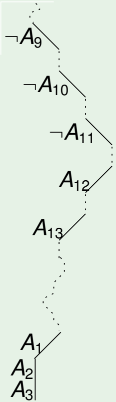

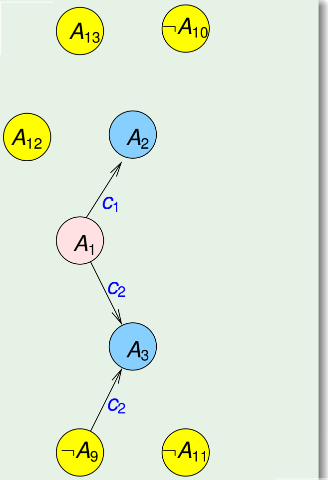

$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ..., A_1, A_2, A_3\}$
(unit A_2, A_3)

Example

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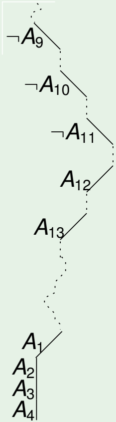

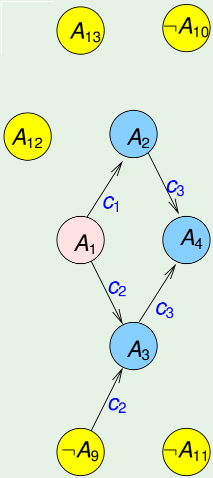

$\{\ldots, \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, \ldots, A_1, A_2, A_3, A_4\}$

(unit A_4)

Example

$c_1 : \neg A_1 \vee A_2$ ✓

$c_2 : \neg A_1 \vee A_3 \vee A_9$ ✓

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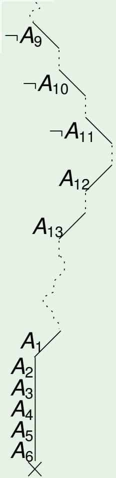

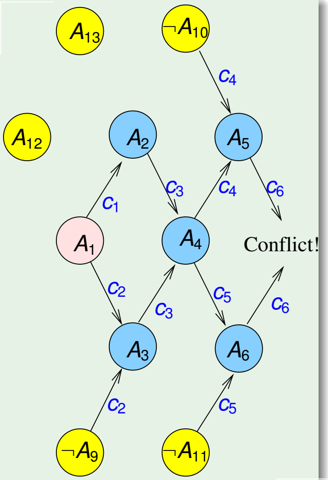

$\{\ldots, \neg A_9, \neg A_{10}, \neg A_1{}_{\neg A_4}1, A_{12}, A_{13}, \ldots, A_1, A_2, A_3, A_4, A_5, A_6\}$

(unit A_5, A_6) $\Longrightarrow$ conflict

Unique implication point - UIP [44]

- A node *l* in an implication graph is an unique implication point (UIP) for the last decision level iff every path from the last decision node to both the conflict nodes passes through *l*.
  - the most recent decision node is an UIP (last UIP)
  - all other UIP's have been assigned after the most recent decision

Unique implication point - UIP - example

$c_1 : \neg A_1 \vee A_2$ √

$c_2 : \neg A_1 \vee A_3 \vee A_9$ √

$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$ √

$c_4 : \neg A_4 \vee A_5 \vee A_{10}$ √

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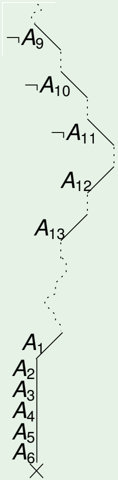

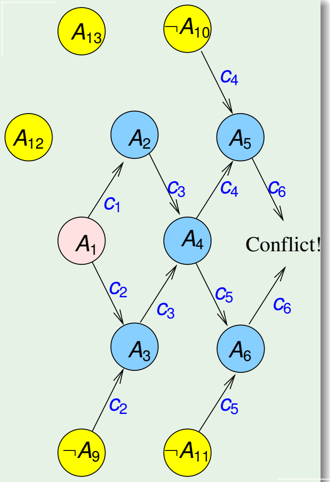

- A_1 is the last UIP
- A_4 is the 1^{st} UIP

Schema of a CDCL DPLL solver [38, 45]

```
Function CDCL-SAT (formula: φ, assignment & μ) {
        status := preprocess(φ,μ);
        while (1) {
            while (1) {
                status := deduce(φ,μ);
                if (status == Sat)
                    return Sat;
                if (status == Conflict) {
                    ⟨blevel,η⟩ := analyze_conflict(φ,μ);
                    //η is a conflict set
                    if (blevel == 0)
                        return Unsat;
                    else backtrack(blevel,φ,μ);
                }
                else break;
            }
            decide_next_branch(φ,μ);
}       }
```

Schema of a CDCL DPLL solver [38, 45] (cont.)

- `preprocess(`φ, μ`)` simplifies φ into an easier equisatisfiable formula, updating μ.
- `decide_next_branch(`φ, μ`)` chooses a new decision literal from φ according to some heuristic, and adds it to μ
- `deduce(`φ, μ`)` performs all deterministic assignments (unit-propagations plus others), and updates φ, μ accordingly.
- `analyze_conflict(`φ, μ`)` Computes the subset η of μ causing the conflict (conflict set), and returns the "wrong-decision" level suggested by η ("0" means that η is entirely assigned at level 0, i.e., a conflict exists even without branching);
- `backtrack(blevel,`φ, μ`)` undoes the branches up to blevel, and updates φ, μ accordingly

Backjumping and learning: general ideas [2, 38]

- When a branch μ fails:
  - (i) conflict analysis: reveal the sub-assignment $\eta \subseteq \mu$ causing the failure (conflict set η)
  - (ii) learning: add the conflict clause $C \stackrel{\text{def}}{=} \neg\eta$ to the clause set
  - (iii) backjumping: use η to decide the point where to backtrack
- Jump back up much more than one decision level in the stack $\Longrightarrow$ may avoid lots of redundant search!!.
- We illustrate two main backjumping & learning strategies:
  - the original strategy presented in [38]
  - the state-of-the-art 1^{st}UIP strategy of [44]

Conflict analysis

1. $C :=$ falsified clause (conflicting clause)
2. repeat

   (i) resolve the current clause C with the antecedent clause of the last unit-propagated literal l in C

   until C verifies some given termination criteria

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criterion: decision

...until C contains only decision literals

$$
\dfrac{\neg A_1 \vee A_2 \qquad \dfrac{\neg A_1 \vee A_3 \vee A_9 \qquad \dfrac{\neg A_2 \vee \neg A_3 \vee A_4 \qquad \dfrac{\neg A_4 \vee A_5 \vee A_{10} \qquad \dfrac{\neg A_4 \vee A_6 \vee A_{11} \qquad \overbrace{\neg A_5 \vee \neg A_6}^{\textit{Conflicting cl.}}}{\neg A_4 \vee \neg A_5 \vee A_{11}}\,(A_6)}{\neg A_4 \vee A_{10} \vee A_{11}}\,(A_5)}{\neg A_2 \vee \neg A_3 \vee A_{10} \vee A_{11}}\,(A_4)}{\neg A_2 \vee \neg A_1 \vee A_9 \vee A_{10} \vee A_{11}}\,(A_3)}{\neg A_1 \vee A_9 \vee A_{10} \vee A_{11}}\,(A_2)
$$

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1. $C :=$ falsified clause (conflicting clause)
2. repeat
   (i) resolve the current clause C with the antecedent clause of the last unit-propagated literal l in C

   until C verifies some given termination criteria

criterion: last UIP

... until C contains only one literal assigned at current decision level: the decision literal (last UIP)

$$\dfrac{\neg A_4 \lor A_6 \lor A_{11} \qquad \overbrace{\neg A_5 \lor \neg A_6}^{\textit{Conflicting cl.}}}{\neg A_4 \lor \neg A_5 \lor A_{11}}\ (A_6)$$

$$\dfrac{\neg A_4 \lor A_5 \lor A_{10} \qquad \neg A_4 \lor \neg A_5 \lor A_{11}}{\neg A_4 \lor A_{10} \lor A_{11}}\ (A_5)$$

$$\dfrac{\neg A_2 \lor \neg A_3 \lor A_4 \qquad \neg A_4 \lor A_{10} \lor A_{11}}{\neg A_2 \lor \neg A_3 \lor A_{10} \lor A_{11}}\ (A_4)$$

$$\dfrac{\neg A_1 \lor A_3 \lor A_9 \qquad \neg A_2 \lor \neg A_3 \lor A_{10} \lor A_{11}}{\neg A_2 \lor \neg A_1 \lor A_9 \lor A_{10} \lor A_{11}}\ (A_3)$$

$$\dfrac{\neg A_1 \lor A_2 \qquad \neg A_2 \lor \neg A_1 \lor A_9 \lor A_{10} \lor A_{11}}{\neg A_1 \lor A_9 \lor A_{10} \lor A_{11}}\ (A_2)$$

Conflict analysis

1. $C :=$ falsified clause (conflicting clause)
2. repeat
   (i) resolve the current clause C with the antecedent clause of the last unit-propagated literal l in C

   until C verifies some given termination criteria

criterion: 1st UIP

... until C contains only one literal assigned at current decision level (1st UIP)

$$\dfrac{\neg A_4 \vee A_5 \vee A_{10} \qquad \dfrac{\neg A_4 \vee A_6 \vee A_{11} \qquad \overbrace{\neg A_5 \vee \neg A_6}^{Conflicting\ cl.}}{\neg A_4 \vee \neg A_5 \vee A_{11}}\ (A_6)}{\underbrace{\neg A_4}_{1st\ UIP} \vee A_{10} \vee A_{11}}\ (A_5)$$

Conflict analysis

1. $C :=$ falsified clause (conflicting clause)
2. repeat

   (i) resolve the current clause C with the antecedent clause of the last unit-propagated literal l in C

   until C verifies some given termination criteria

Note:

$\varphi \models C$, so that C can be safely added to C.

Note:

Equivalent to finding a partition in the implication graph of μ with all decision literals on one side and the conflict on the other.

Conflict analysis

1. $C :=$ falsified clause (conflicting clause)
2. repeat

   (i) resolve the current clause C with the antecedent clause of the last unit-propagated literal l in C

   until C verifies some given termination criteria

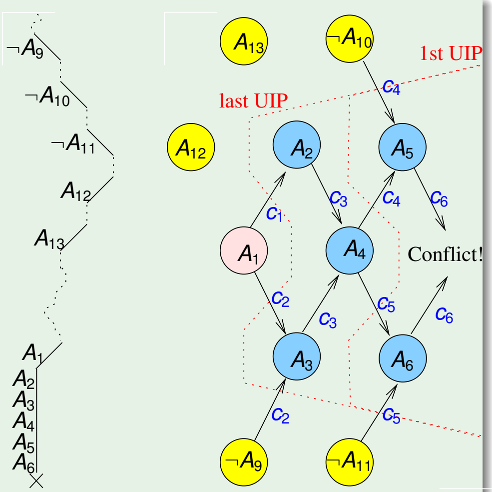
Note:

$\varphi \models C$, so that C can be safely added to C.

Note:

Equivalent to finding a partition in the implication graph of μ with all decision literals on one side and the conflict on the other.

$c_1 : \neg A_1 \lor A_2$ √
$c_2 : \neg A_1 \lor A_3 \lor A_9$ √
$c_3 : \neg A_2 \lor \neg A_3 \lor A_4$ √
$c_4 : \neg A_4 \lor A_5 \lor A_{10}$ √
$c_5 : \neg A_4 \lor A_6 \lor A_{11}$ √
$c_6 : \neg A_5 \lor \neg A_6$ ×
$c_7 : A_1 \lor A_7 \lor \neg A_{12}$ √
$c_8 : A_1 \lor A_8$ √
$c_9 : \neg A_7 \lor \neg A_8 \lor \neg A_{13}$
...



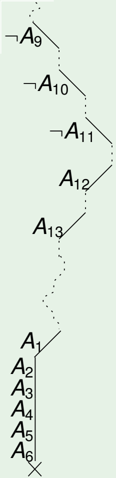
Note: in this case decision and last-UIP criteria produce the same partition

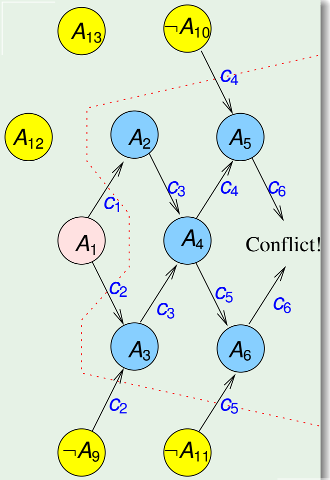
The original backjumping and learning strategy of [38]

- Idea: when a branch μ fails,
  (i) conflict analysis: find the conflict set $\eta \subseteq \mu$ by generating the conflict clause $C \stackrel{\text{def}}{=} \neg\eta$ via resolution from the falsified clause (conflicting clause) using the "Decision" criterion;
  (ii) learning: add the conflict clause C to the clause set
  (iii) backjumping: backtrack to the most recent branching point s.t. the stack does not fully contain η, and then unit-propagate the unassigned literal on C

The Original Backjumping Strategy: Example

$c_1 : \neg A_1 \vee A_2$ √
$c_2 : \neg A_1 \vee A_3 \vee A_9$ √
$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$ √
$c_4 : \neg A_4 \vee A_5 \vee A_{10}$ √
$c_5 : \neg A_4 \vee A_6 \vee A_{11}$ √
$c_6 : \neg A_5 \vee \neg A_6$ ×
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$ √
$c_8 : A_1 \vee A_8$ √
$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$
...

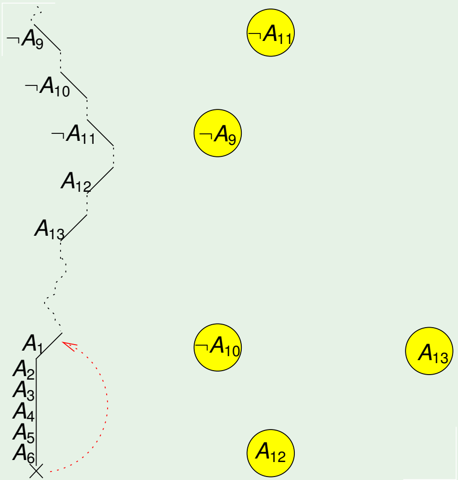




$\Longrightarrow$ Conflict set: $\{\neg A_9, \neg A_{10}, \neg A_{11}, A_1\}$ ("decision" schema)
$\Longrightarrow$ learn the conflict clause $c_{10} := A_9 \vee A_{10} \vee A_{11} \vee \neg A_1$

The Original Backjumping Strategy: Example

$c_1 : \neg A_1 \vee A_2$
$c_2 : \neg A_1 \vee A_3 \vee A_9$
$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$
$c_4 : \neg A_4 \vee A_5 \vee A_{10}$
$c_5 : \neg A_4 \vee A_6 \vee A_{11}$
$c_6 : \neg A_5 \vee \neg A_6$
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$
$c_8 : A_1 \vee A_8$
$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$
$c_{10} : A_9 \vee A_{10} \vee A_{11} \vee \neg A_1$
...



$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ...\}$
$\Longrightarrow$ backtrack up to A_1

The Original Backjumping Strategy: Example

$c_1 : \neg A_1 \vee A_2$ √

$c_2 : \neg A_1 \vee A_3 \vee A_9$ √

$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$

$c_4 : \neg A_4 \vee A_5 \vee A_{10}$

$c_5 : \neg A_4 \vee A_6 \vee A_{11}$

$c_6 : \neg A_5 \vee \neg A_6$

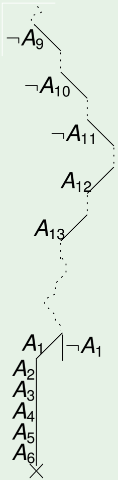
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$

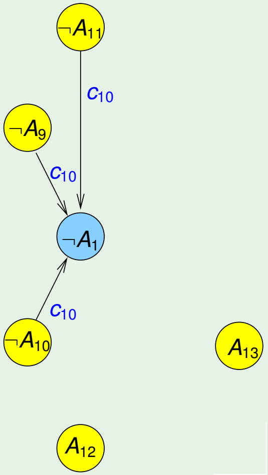
$c_8 : A_1 \vee A_8$

$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$

$c_{10} : A_9 \vee A_{10} \vee A_{11} \vee \neg A_1$ √

...

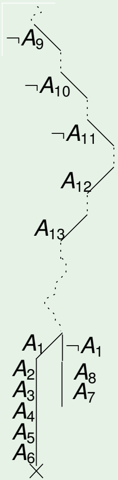


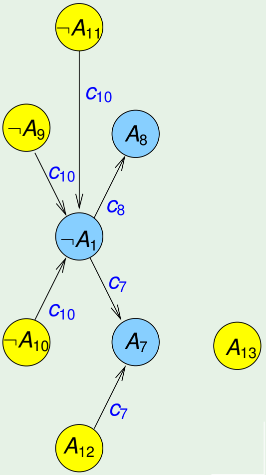


$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ..., \neg A_1\}$
(unit $\neg A_1$)

The Original Backjumping Strategy: Example

$c_1 : \neg A_1 \vee A_2$ √
$c_2 : \neg A_1 \vee A_3 \vee A_9$ √
$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$
$c_4 : \neg A_4 \vee A_5 \vee A_{10}$
$c_5 : \neg A_4 \vee A_6 \vee A_{11}$
$c_6 : \neg A_5 \vee \neg A_6$
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$ √
$c_8 : A_1 \vee A_8$ √
$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$
$c_{10} : A_9 \vee A_{10} \vee A_{11} \vee \neg A_1$ √
...





$\{\ldots, \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, \ldots, \neg A_1, A_7, A_8\}$
(unit A_7, A_8)

The Original Backjumping Strategy: Example

$c_1 : \neg A_1 \vee A_2$ √

$c_2 : \neg A_1 \vee A_3 \vee A_9$ √

$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$

$c_4 : \neg A_4 \vee A_5 \vee A_{10}$

$c_5 : \neg A_4 \vee A_6 \vee A_{11}$

$c_6 : \neg A_5 \vee \neg A_6$

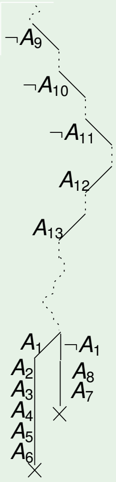
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$ √

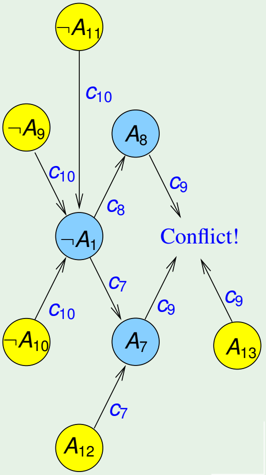
$c_8 : A_1 \vee A_8$ √

$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$ ×

$c_{10} : A_9 \vee A_{10} \vee A_{11} \vee \neg A_1$ √

...





$\{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}, ..., \neg A_1, A_7, A_8\}$

Conflict!

The Original Backjumping Strategy: Example

c_1 : $\neg A_1 \vee A_2$ ✓

c_2 : $\neg A_1 \vee A_3 \vee A_9$ ✓

c_3 : $\neg A_2 \vee \neg A_3 \vee A_4$

c_4 : $\neg A_4 \vee A_5 \vee A_{10}$

c_5 : $\neg A_4 \vee A_6 \vee A_{11}$

c_6 : $\neg A_5 \vee \neg A_6$

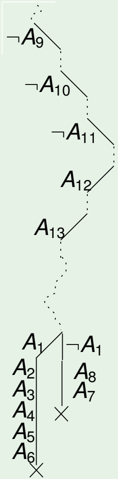
c_7 : $A_1 \vee A_7 \vee \neg A_{12}$ ✓

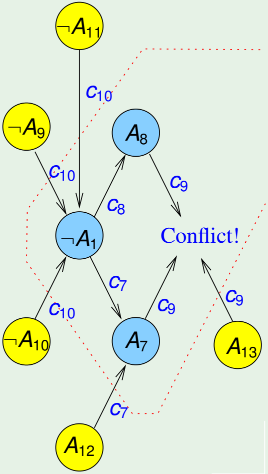
c_8 : $A_1 \vee A_8$ ✓

c_9 : $\neg A_7 \vee \neg A_8 \vee \neg A_{13}$ ×

c_{10} : $A_9 \vee A_{10} \vee A_{11} \vee \neg A_1$ ✓

...



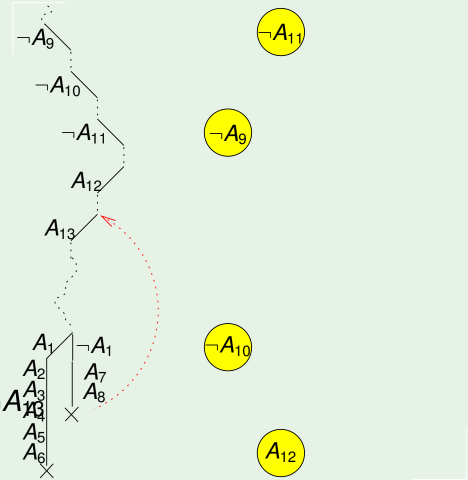


$\Longrightarrow$ conflict set: $\{\neg A_9, \neg A_{10}, \neg A_{11}, A_{12}, A_{13}\}$.

$\Longrightarrow$ learn $C_{11} := A_9 \vee A_{10} \vee A_{11} \vee \neg A_{12} \vee \neg A_{13}$

The Original Backjumping Strategy: Example

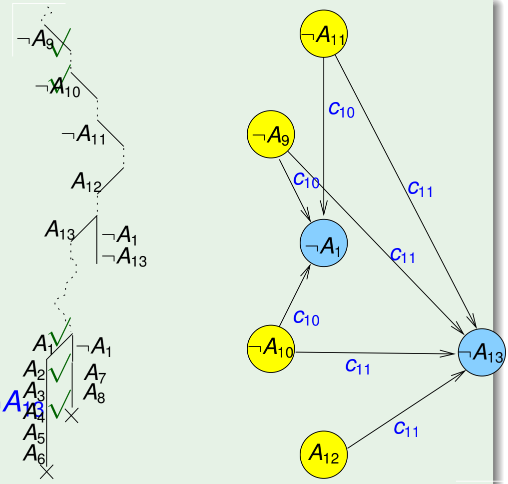
$c_1 : \neg A_1 \vee A_2$
$c_2 : \neg A_1 \vee A_3 \vee A_9$
$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$
$c_4 : \neg A_4 \vee A_5 \vee A_{10}$
$c_5 : \neg A_4 \vee A_6 \vee A_{11}$
$c_6 : \neg A_5 \vee \neg A_6$
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$
$c_8 : A_1 \vee A_8$
$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$
$c_{10} : A_9 \vee A_{10} \vee A_{11} \vee \neg A_1$
$c_{11} : A_9 \vee A_{10} \vee A_{11} \vee \neg A_{12} \vee \neg A_{13}$
...



$\Longrightarrow$ backtrack to A_{13} $\Longrightarrow$ Lots of search saved!

The Original Backjumping Strategy: Example

$c_1 : \neg A_1 \vee A_2$
$c_2 : \neg A_1 \vee A_3 \vee A_9$
$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$
$c_4 : \neg A_4 \vee A_5 \vee A_{10}$
$c_5 : \neg A_4 \vee A_6 \vee A_{11}$
$c_6 : \neg A_5 \vee \neg A_6$
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$
$c_8 : A_1 \vee A_8$
$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$
$c_{10} : A_9 \vee A_{10} \vee A_{11} \vee \neg A_1$
$c_{11} : A_9 \vee A_{10} \vee A_{11} \vee \neg A_{12} \vee \neg A_{13}$
...



$\Longrightarrow$ backtrack to A_{13}, then set A_{13} and A_1 to $\perp$,...

State-of-the-art backjumping and learning [44]

- Idea: when a branch μ fails,
  (i) conflict analysis: find the conflict set $\eta \subseteq \mu$ by generating the conflict clause $C \stackrel{\text{def}}{=} \neg\eta$ via resolution from the falsified clause, according to the 1^{st}UIP strategy
  (ii) learning: add the conflict clause C to the clause set
  (iii) backjumping: backtrack to the highest branching point s.t. the stack contains all-but-one literals in η, and then unit-propagate the unassigned literal on C

1st UIP strategy – example (7)

$c_1 : \neg A_1 \vee A_2$ ✓

$c_2 : \neg A_1 \vee A_3 \vee A_9$ ✓

$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$ ✓

$c_4 : \neg A_4 \vee A_5 \vee A_{10}$ ✓

$c_5 : \neg A_4 \vee A_6 \vee A_{11}$ ✓

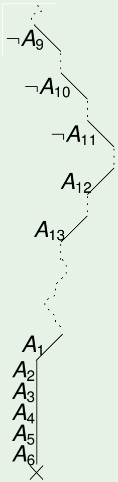
$c_6 : \neg A_5 \vee \neg A_6$ ×

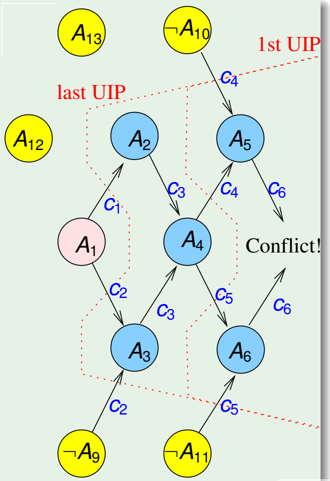
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$ ✓

$c_8 : A_1 \vee A_8$ ✓

$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$

...





$\Longrightarrow$ Conflict set: $\{\neg A_{10}, \neg A_{11}, A_4\}$, learn $c_{10} := A_{10} \vee A_{11} \vee \neg A_4$

1st UIP strategy and backjumping [44]

- The added conflict clause states the reason for the conflict
- The procedure backtracks to the most recent decision level of the variables in the conflict clause which are not the UIP.
- then the conflict clause forces the negation of the UIP by unit propagation.

E.g.: $c_{10} := A_{10} \vee A_{11} \vee \neg A_4$
$\Longrightarrow$ backtrack to A_{11}, then assign $\neg A_4$

1st UIP strategy – example (7)

$c_1 : \neg A_1 \lor A_2$ ✓

$c_2 : \neg A_1 \lor A_3 \lor A_9$ ✓

$c_3 : \neg A_2 \lor \neg A_3 \lor A_4$ ✓

$c_4 : \neg A_4 \lor A_5 \lor A_{10}$ ✓

$c_5 : \neg A_4 \lor A_6 \lor A_{11}$ ✓

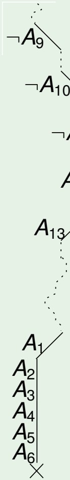
$c_6 : \neg A_5 \lor \neg A_6$ ×

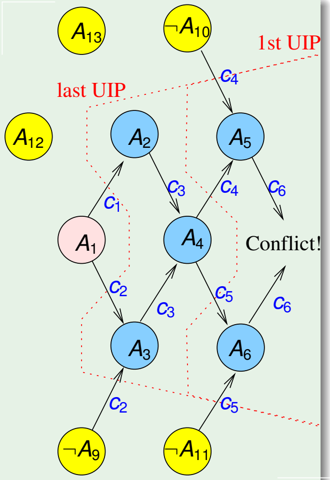
$c_7 : A_1 \lor A_7 \lor \neg A_{12}$ ✓

$c_8 : A_1 \lor A_8$ ✓

$c_9 : \neg A_7 \lor \neg A_8 \lor \neg A_{13}$

...

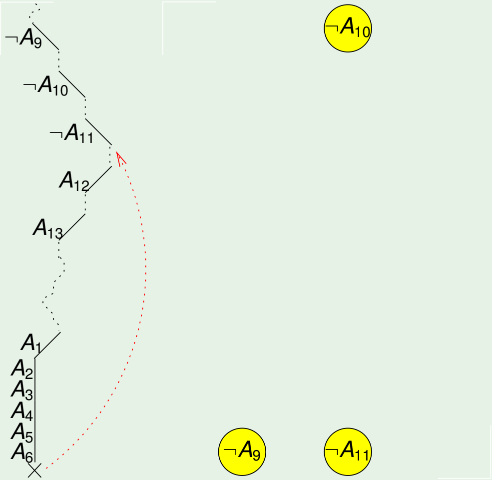




$\Longrightarrow$ Conflict set: $\{\neg A_{10}, \neg A_{11}, A_4\}$, learn $c_{10} := A_{10} \lor A_{11} \lor \neg A_4$

1st UIP strategy – example (8)

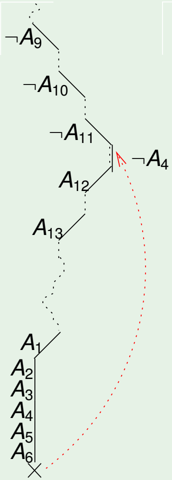
$c_1 : \neg A_1 \vee A_2$
$c_2 : \neg A_1 \vee A_3 \vee A_9$
$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$
$c_4 : \neg A_4 \vee A_5 \vee A_{10}$
$c_5 : \neg A_4 \vee A_6 \vee A_{11}$
$c_6 : \neg A_5 \vee \neg A_6$
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$
$c_8 : A_1 \vee A_8$
$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$
$c_{10} : A_{10} \vee A_{11} \vee \neg A_4$
...

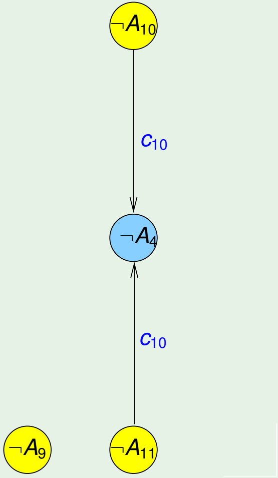


$\Longrightarrow$ backtrack up to $A_{11} \Longrightarrow \{..., \neg A_9, \neg A_{10}, \neg A_{11}\}$

1st UIP strategy – example (9)

$c_1 : \neg A_1 \vee A_2$
$c_2 : \neg A_1 \vee A_3 \vee A_9$
$c_3 : \neg A_2 \vee \neg A_3 \vee A_4$
$c_4 : \neg A_4 \vee A_5 \vee A_{10}$ $\surd$
$c_5 : \neg A_4 \vee A_6 \vee A_{11}$ $\surd$
$c_6 : \neg A_5 \vee \neg A_6$
$c_7 : A_1 \vee A_7 \vee \neg A_{12}$
$c_8 : A_1 \vee A_8$
$c_9 : \neg A_7 \vee \neg A_8 \vee \neg A_{13}$
$c_{10} : A_{10} \vee A_{11} \vee \neg A_4$ $\surd$
...





$\Longrightarrow$ unit propagate $\neg A_4 \Longrightarrow \{..., \neg A_9, \neg A_{10}, \neg A_{11}, A_4\}$...

1st UIP strategy and backjumping – intuition

- An UIP is a single reason implying the conflict at the current level
- substituting the 1st UIP for the last UIP
  - does not enlarge the conflict
  - requires less resolution steps to compute C
  - may require involving less decision literals from other levels
- by backtracking to the most recent decision level of the variables in the conflict clause which are not the UIP:
  - jump higher
  - allows for assigning (the negation of) the UIP as high as possible in the search tree.

Learning [2, 38]

Idea: When a conflict set η is revealed, then $C \stackrel{\text{def}}{=} \neg\eta$ added to φ
$\Longrightarrow$ the solver will no more generate an assignment containing η: when $|\eta| - 1$ literals in η are assigned, the other is set $\perp$ by unit-propagation on C
$\Longrightarrow$ Drastic pruning of the search!

Learning – example

$c_1 : \neg A_1 \lor A_2$

$c_2 : \neg A_1 \lor A_3 \lor A_9$

$c_3 : \neg A_2 \lor \neg A_3 \lor A_4$

$c_4 : \neg A_4 \lor A_5 \lor A_{10}$

$c_5 : \neg A_4 \lor A_6 \lor A_{11}$

$c_6 : \neg A_5 \lor \neg A_6$

$c_7 : A_1 \lor A_7 \lor \neg A_{12}$

$c_8 : A_1 \lor A_8$

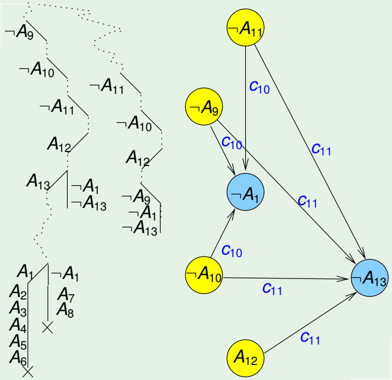
$c_9 : \neg A_7 \lor \neg A_8 \lor \neg A_{13}$ √

$c_{10} : A_9 \lor A_{10} \lor A_{11} \lor \neg A_1$ √

$c_{11} : A_9 \lor A_{10} \lor A_{11} \lor \neg A_{12} \lor \neg A_{13}$ √

...

$\Longrightarrow$ Unit: $\{\neg A_1, \neg A_{13}\}$



Drawbacks of Learning & Clause discharging

Problem with Learning

Learning can generate exponentially-many clauses

- may cause a blowup in space
- may drastically slow down BCP

A solution: clause discharging

Techniques to drop learned clauses when necessary

- according to their size
- according to their activity.

A clause is currently active if it occurs in the current implication graph (i.e., it is the antecedent clause of a literal in the current assignment).

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Drawbacks of Learning & Clause discharging

- Is clause-discharging safe?
- Yes, if done properly.

Property (see, e.g., [30])

In order to guarantee correctness, completeness & termination of a CDCL solver, it suffices to keep each clause until it is active.
$\Longrightarrow$ CDCL solvers require polynomial space

“Lazy” Strategy

- when a clause is involved in conflict analisis, increase its activity
- when needed, drop the least-active clauses

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- Yes, if done properly.

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$\Longrightarrow$ CDCL solvers require polynomial space

"Lazy" Strategy

- when a clause is involved in conflict analisis, increase its activity
- when needed, drop the least-active clauses

Drawbacks of Learning & Clause discharging

- Is clause-discharging safe?
- Yes, if done properly.

Property (see, e.g., [30])

In order to guarantee correctness, completeness & termination of a CDCL solver, it suffices to keep each clause until it is active.
$\Longrightarrow$ CDCL solvers require polynomial space

"Lazy" Strategy

- when a clause is involved in conflict analisis, increase its activity
- when needed, drop the least-active clauses

State-of-the-art backjumping and learning: intuitions

- Backjumping: allows for climbing up to many decision levels in the stack
  - intuition: " go back to the oldest decision where you'd have done something different if only you had known C"

  $\Longrightarrow$ may avoid lots of redundant search
- Learning: in future branches, when all-but-one literals in η are assigned, the remaining literal is assigned to false by unit-propagation:
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Remark: the “quality” of conflict sets

- Different ideas of “good” conflict set
  - Backjumping: if causes the highest backjump (“local” role)
  - Learning: if causes the maximum pruning (“global” role)
- Many different strategies implemented (see, e.g., [2, 38, 44])

Outline

Preprocessing/Inprocessing

- Part of `preprocess()` and `deduce()` steps respectively
- Simplify current formula into an equivalently-satisfiable one
- Must be fast (in particular inprocessing)
- Some techniques:
  - detect and remove subsumed clauses
  - detect & collapse equivalent literals
  - apply basic resolution steps
  - ...

Preprocessing/Inprocessing (cont.)

Detect and remove subsumed clauses:

$$\varphi_1 \wedge (l_2 \vee l_1) \wedge \varphi_2 \wedge (l_2 \vee l_3 \vee l_1) \wedge \varphi_3$$
$$\Downarrow$$
$$\varphi_1 \wedge (l_1 \vee l_2) \wedge \varphi_2 \wedge \varphi_3$$

Preprocessing/Inprocessing (cont.)

Detect & collapse equivalent literals [7]

Repeat:

(i) build the implication graph induced by binary clauses

(ii) detect strongly connected cycles $\Longrightarrow$ equivalence classes of literals

(iii) perform substitutions

(iv) perform unit and pure literal.

Until (no more simplification is possible).

- Ex:

$$\varphi_1 \wedge (\neg l_2 \vee l_1) \wedge \varphi_2 \wedge (\neg l_3 \vee l_2) \wedge \varphi_3 \wedge (\neg l_1 \vee l_3) \wedge \varphi_4$$
$$\Downarrow_{l_1 \leftrightarrow l_2 \leftrightarrow l_3}$$
$$(\varphi_1 \wedge \varphi_2 \wedge \varphi_3 \wedge \varphi_4)[l_2 \leftarrow l_1; l_3 \leftarrow l_1;]$$

- Very effective in many application domains.

Preprocessing/Inprocessing (cont.)

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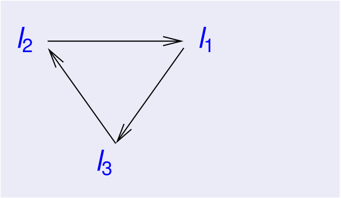

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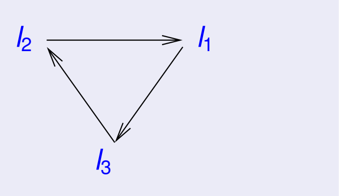

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Preprocessing/Inprocessing (cont.)

Apply some basic steps of resolution (and simplify)

$$\varphi_1 \wedge (l_2 \vee l_1) \wedge \varphi_2 \wedge (l_2 \vee \neg l_1) \wedge \varphi_3$$
$$\Downarrow_{resolve}$$
$$\varphi_1 \wedge (l_2) \wedge \varphi_2 \wedge \varphi_3$$
$$\Downarrow_{unit-propagate}$$
$$(\varphi_1 \wedge \varphi_2 \wedge \varphi_3)[l_2 \leftarrow \top]$$

Literal-Decision Heuristics (aka Branching Heuristics)

- Implemented in `decide_next_branch()`
- Branch is the source of non-determinism for DPLL
  $\Longrightarrow$ critical for efficiency
- Many literal-decision heuristics in literature (for DPLL & CDCL)

Some Heuristics

- MOMS heuristics (DPLL): pick the literal occurring most often in the minimal size clauses
  $\Longrightarrow$ fast and simple, many variants
- Jeroslow-Wang (DPLL): choose the literal with maximum

$$score(l) := \Sigma_{l \in c \ \& \ c \in \varphi} 2^{-|c|}$$

  $\Longrightarrow$ estimates l's contribution to the satisfiability of φ
- Satz [21] (DPLL): selects a candidate set of literals, perform unit propagation, chooses the one leading to smaller clause set
  $\Longrightarrow$ maximizes the effects of unit propagation
- VSIDS [28] (CDCL+): variable state independent decaying sum
  - "static": scores updated only at the end of a branch
  - "local": privileges variable in recently learned clauses

Restarts [16]

Idea: (according to some strategy) restart the search

- abandon the current search tree and reconstruct a new one
- The clauses learned prior to the restart are still there after the restart and can help pruning the search space
- avoid getting stuck in certain areas of the search space

$\Longrightarrow$ may significantly reduce the overall search space

Outline

SAT under assumptions: $SAT(\varphi, \{l_1, ..., l_n\})$ [12]

- Many SAT solvers allow for solving a CNF formula φ under a set of assumption literals $\mathcal{A} \stackrel{\text{def}}{=} \{l_1, ..., l_n\}$: $SAT(\varphi, \{l_1, ..., l_n\})$
  - $SAT(\varphi, \{l_1, ..., l_n\})$: same result as $SAT(\varphi \wedge \bigwedge_{i=1}^{n} l_i)$
  - often useful to call the same formula with different assumption lists: $SAT(\varphi, \mathcal{A}_1), SAT(\varphi, \mathcal{A}_2), ...$
- Idea:
  - $l_1, ..., l_n$ "decided" at decision level 0 before starting the search
  - if backjump to level 0 on $C \stackrel{\text{def}}{=} \neg\eta$ s.t. $\eta \subseteq \mathcal{A}$, then return UNSAT

Property

If the "decision" strategy for conflict analysis is used,
then η is the subset of assumptions causing the inconsistency

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Selection of sub-formulas

Idea: select clauses [12, 23]

Let φ be $\bigwedge_{i=1}^{n} C_i$.

- let $S_1 ... S_n$ be fresh Boolean atoms (selection variables).
- let $\mathcal{A} \stackrel{\text{def}}{=} \{S_{i_1}, ..., S_{i_K}\} \subseteq \{S_1, ..., S_n\}$

$\Longrightarrow$ SAT($\bigwedge_{i=1}^{n}(\neg S_i \vee C_i), \mathcal{A}$): same as SAT($\bigwedge_{i=i_1}^{i_k}(C_i)$)

- if S_i is not assumed, then $\neg S_i \vee C_i$ does not contribute to search

$\Longrightarrow$ "Select" (activate) only a subset of the clauses in φ at each call.

Generalised Idea: select blocks of clauses

Let φ be $\bigwedge_{i=1}^{n}(\bigwedge_{j=1}^{n_i} C_{ij})$.

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Example

- Initial formula φ:
  $(\ A_1 \ \vee\neg A_2 \ \vee\neg A_3 \ )\wedge$ // *group* 1
  $(\neg A_3 \ \vee\ A_2 \ \vee\neg A_5 \ )\wedge$ // *group* 1
  $(\neg A_2 \ \vee\ A_5 \ \vee\ A_7 \ )\wedge$ // *group* 2
  $(\ A_3 \ \vee\ A_5 \ \vee\neg A_8 \ )\wedge$ // *group* 2
  $(\neg A_1 \ \vee\neg A_3 \ \vee\ A_8 \ )\wedge$ // *group* 3
- Augmented formula φ':
  $(\neg S_1 \ \vee\ A_1 \ \vee\neg A_2 \ \vee\neg A_3 \ )\wedge$ // *group* 1, *inactive*
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  $(\neg S_2 \ \vee\ A_2 \ \vee\ A_5 \ \vee\neg A_8 \ )\wedge$ // *group* 2, *inactive*
  $(\neg S_3 \ \vee\neg A_1 \ \vee\neg A_3 \ \vee\ A_8 \ )\wedge$ // *group* 3
- $SAT(\varphi', \{S_2, S_3\})$: activates group 2,3
- $SAT(\varphi', \{S_1, S_3\})$: activates group 1,3

Example

- Initial formula φ:

$$(\ A_1 \ \lor\neg A_2 \ \lor\neg A_3 \ )\land \quad // \textit{ group } 1$$
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\begin{array}{llllll}
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(\neg S_1 & \vee\neg A_3 & \vee\ A_2 & \vee\neg A_5 &)\wedge & //\ group\ 1,\ inactive \\
(\neg S_2 & \vee\neg A_2 & \vee\ A_5 & \vee\ A_7 &)\wedge & //\ group\ 2,\ inactive \\
(\neg S_2 & \vee\ A_2 & \vee\ A_5 & \vee\neg A_8 &)\wedge & //\ group\ 2,\ inactive \\
(\neg S_3 & \vee\neg A_1 & \vee\neg A_3 & \vee\ A_8 &)\wedge & //\ group\ 3
\end{array}
$$

- $SAT(\varphi', \{S_2, S_3\})$: activates group 2,3
- $SAT(\varphi', \{S_1, S_3\})$: activates group 1,3

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  $(\ A_1 \ \vee\neg A_2 \ \vee\neg A_3\ )\wedge$ // *group* 1
  $(\neg A_3 \ \vee\ A_2 \ \vee\neg A_5\ )\wedge$ // *group* 1
  $(\neg A_2 \ \vee\ A_5 \ \vee\ A_7\ )\wedge$ // *group* 2
  $(\ A_3 \ \vee\ A_5 \ \vee\neg A_8\ )\wedge$ // *group* 2
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Incremental SAT solving [12, 11]

- Many CDCL solvers provide a stack-based incremental interface
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- Maintains the status of the search from one call to the other
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Example

- Initial formula φ:

$$\begin{array}{llllll} \ldots & & & & \wedge & \\ (& A_1 & \vee\neg A_2 & \vee\neg A_3 &)\wedge & // \ \phi_1 \\ (\neg A_3 & \vee & A_2 & \vee\neg A_5 &)\wedge & // \ \phi_1 \end{array}$$

- Augmented formula φ':

$$\begin{array}{lllllll} \ldots & & & & & \wedge & \\ (\neg S_1 & \vee & A_1 & \vee\neg A_2 & \vee\neg A_3 &)\wedge & // \ \phi_1 \\ (\neg S_1 & \vee\neg A_3 & \vee & A_2 & \vee\neg A_5 &)\wedge & // \ \phi_1 \end{array}$$

[push(S_1)]: $SAT(\varphi', \{..., S_1\})$: ϕ_1 active $\Longrightarrow$ learn C_1 from ϕ_1

- C_1 derived from $\phi_1 \Longrightarrow C_1$ active only when ϕ_1 is active
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\end{array}
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$$
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Outline

Advanced functionalities

Advanced SAT functionalities (very important in formal verification):

- Building proofs of unsatisfiability
- Extracting unsatisfiable Cores
- Computing Craig Interpolants
- Optimization in SAT: MaxSAT (hints)
- Enumeration on SAT: All-SAT and Model Counting (hints)

Building Proofs of Unsatisfiability

- When φ is unsat, it is very important to build a (resolution) proof of unsatisfiability:
  - to verify the result of the solver
  - to understand a "reason" for unsatisfiability
  - to build unsatisfiable cores and interpolants
- Can be built by keeping track of the resolution steps performed when constructing the conflict clauses.

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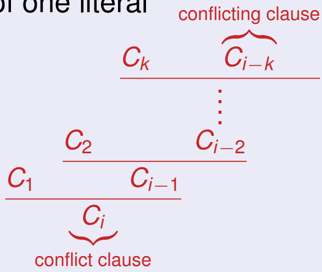

- C_1, ..., C_k, and C_{i-k} can be original or learned clauses
- each resolution (sub)proof can be easily tracked:

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k i-k -> i-k-1
...
2 i-2 -> i-1
1 i-1 -> i
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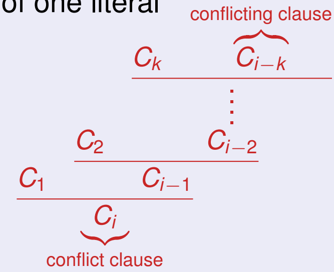

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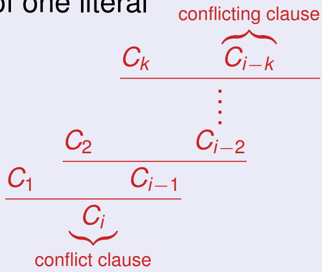

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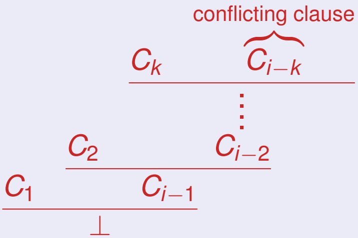
Building Proofs of Unsatisfiability

- ... in particular, if φ is unsatisfiable, the last step produces "false" as conflict clause



(we assume that level-0 literals are also resolved away)

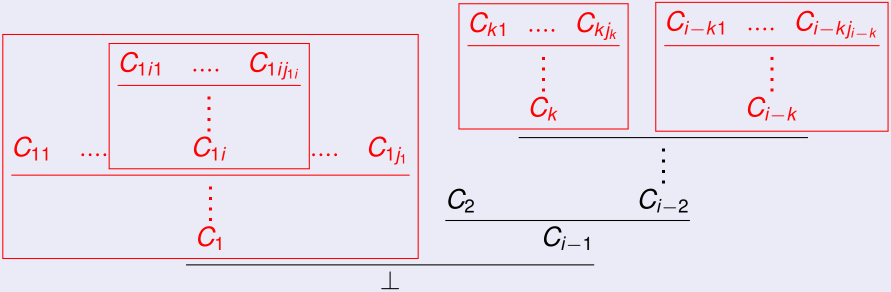
- $C_1 = l$, $C_{i-1} = \neg l$ for some literal l
- $C_1, ..., C_k$, and C_{i-k} can be original or learned clauses...

Building Proofs of Unsatisfiability

Starting from the previous proof of unsatisfiability, repeat recursively:

- for every learned leaf clause C_i, substitute C_i with the resolution proof generating it

until all leaf clauses are original clauses



$\Longrightarrow$ We obtain a resolution proof of unsatisfiability for (a subset of) the clauses in φ

Building Proofs of Unsatisfiability: example

$(B_0 \vee \neg B_1 \vee A_1) \wedge (B_0 \vee B_1 \vee A_2) \wedge (\neg B_0 \vee B_1 \vee A_2) \wedge (\neg B_0 \vee \neg B_1) \wedge (\neg B_2 \vee \neg B_4) \wedge$
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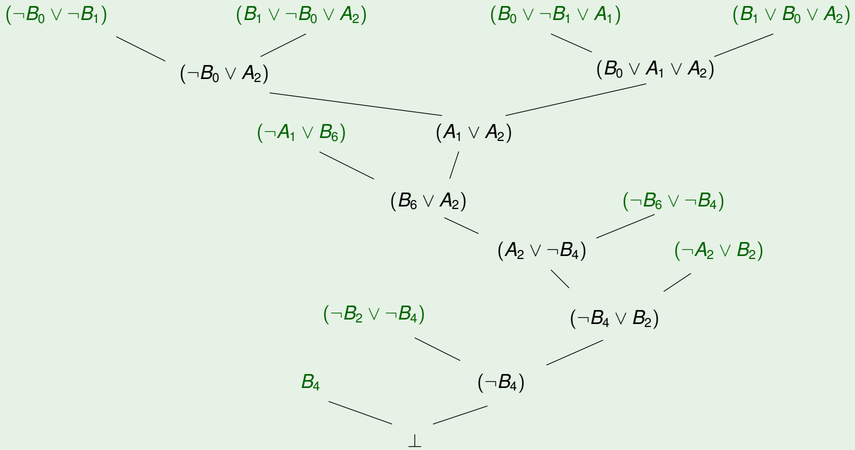

Extraction of unsatisfiable cores

- Problem: given an unsatisfiable set of clauses, extract from it a (possibly small/minimal/minimum) unsatisfiable subset
  $\Longrightarrow$ unsatisfiable cores (aka (Minimal) Unsatisfiable Subsets, (M)US)
- Lots of literature on the topic [46, 24, 26, 31, 43, 19, 13, 6]
- We recognize two main approaches:
  - Proof-based approach [46]: byproduct of finding a resolution proof
  - Assumption-based approach [24]: use extra variables labeling clauses
- Many optimizations for further reducing the size of the core:
  - repeat the process up to fixpoit
  - remove clauses one-by one, until satisfiability is obtained
  - combinations of the two processed above
  - ...

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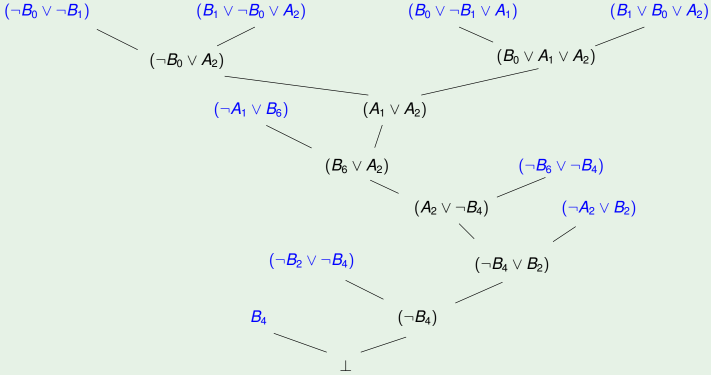
The proof-based approach [46]

Unsat core: the set of leaf clauses of a resolution proof

$$(B_0 \vee \neg B_1 \vee A_1) \wedge (B_0 \vee B_1 \vee A_2) \wedge (\neg B_0 \vee B_1 \vee A_2) \wedge (\neg B_0 \vee \neg B_1) \wedge (\neg B_2 \vee \neg B_4) \wedge$$
$$(\neg A_2 \vee B_2) \wedge (\neg A_1 \vee B_3) \wedge B_4 \wedge (A_2 \vee B_5) \wedge (\neg B_6 \vee \neg B_4) \wedge (B_6 \vee \neg A_1) \wedge B_7$$



The assumption-based approach [24]

Based on the following process:

(i) each clause C_i is substituted by $\neg S_i \vee C_i$, s.t. S_i fresh "selector" variable

(ii) before starting the search each S_i is forced to true.

(iii) final conflict clause at dec. level 0: $\bigvee_j \neg S_j$

$\Longrightarrow$ $\{C_j\}_j$ is the unsat core!

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The assumption-based approach to core extraction

Example

$(B_0 \vee \neg B_1 \vee A_1) \wedge (B_0 \vee B_1 \vee A_2) \wedge (\neg B_0 \vee B_1 \vee A_2) \wedge$
$(\neg B_0 \vee \neg B_1) \wedge (\neg B_2 \vee \neg B_4) \wedge (\neg A_2 \vee B_2) \wedge (\neg A_1 \vee B_3) \wedge$
$B_4 \wedge (A_2 \vee B_5) \wedge (\neg B_6 \vee \neg B_4) \wedge (B_6 \vee \neg A_1) \wedge B_7$

(i) add selector variables:
$(\neg S_1 \vee B_0 \vee \neg B_1 \vee A_1) \wedge (\neg S_2 \vee B_0 \vee B_1 \vee A_2) \wedge (\neg S_3 \vee \neg B_0 \vee B_1 \vee A_2) \wedge$
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$(\neg S_{11} \vee B_6 \vee \neg A_1) \wedge (\neg S_{12} \vee B_7)$

(ii) The conflict analysis returns:
$\neg S_1 \vee \neg S_2 \vee \neg S_3 \vee \neg S_4 \vee \neg S_5 \vee \neg S_6 \vee \neg S_8 \vee \neg S_{10} \vee \neg S_{11},$

(iii) corresponding to the unsat core:
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Computing Craig Interpolants in SAT

Notation: Let "$X \preceq Y$", X, Y being Boolean formulas, denote the fact that all Boolean atoms in X occur also in Y.

Definition: Craig Interpolant

Given an ordered pair (A, B) of formulas such that $A \wedge B \models \bot$, a *Craig interpolant* is a formula I s.t.:

a) $A \models I$,

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- Very important in many Formal Verification applications
- A few works presented [32, 25, 27]

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Computing Craig Interpolants in SAT: a General Algorithm [32]

Algorithm: Interpolant generation (for SAT)

(i) Generate a resolution proof of unsatisfiability $\mathcal{P}$ for $A \wedge B$.

(ii) ...

(iii) For every leaf clause C in $\mathcal{P}$, set $I_C \stackrel{\text{def}}{=} C \downarrow B$ if $C \in A$, and $I_C \stackrel{\text{def}}{=} \top$ if $C \in B$.

(iv) For every inner node C of $\mathcal{P}$ obtained by resolution from $C_1 \stackrel{\text{def}}{=} p \vee \phi_1$ and $C_2 \stackrel{\text{def}}{=} \neg p \vee \phi_2$, set $I_C \stackrel{\text{def}}{=} I_{C_1} \vee I_{C_2}$ if p does not occur in B, and $I_C \stackrel{\text{def}}{=} I_{C_1} \wedge I_{C_2}$ otherwise.

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"$\eta \setminus B$" [resp. "$\eta \downarrow B$"] is the set of literals in η whose atoms do not [resp. do] occur in B.

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(v) Output $I_\bot$ as an interpolant for (A, B).

"$\eta \setminus B$" [resp. "$\eta \downarrow B$"] is the set of literals in η whose atoms do not [resp. do] occur in B.

- optimized versions for the purely-propositional case [25, 27]

Computing Craig Interpolants in SAT: a General Algorithm [32]

Algorithm: Interpolant generation (for SAT)

(i) Generate a resolution proof of unsatisfiability $\mathcal{P}$ for $A \wedge B$.

(ii) ...

(iii) For every leaf clause C in $\mathcal{P}$, set $I_C \stackrel{\text{def}}{=} C \downarrow B$ if $C \in A$, and $I_C \stackrel{\text{def}}{=} \top$ if $C \in B$.

(iv) For every inner node C of $\mathcal{P}$ obtained by resolution from $C_1 \stackrel{\text{def}}{=} p \vee \phi_1$ and $C_2 \stackrel{\text{def}}{=} \neg p \vee \phi_2$, set $I_C \stackrel{\text{def}}{=} I_{C_1} \vee I_{C_2}$ if p does not occur in B, and $I_C \stackrel{\text{def}}{=} I_{C_1} \wedge I_{C_2}$ otherwise.

(v) Output $I_\perp$ as an interpolant for (A, B).

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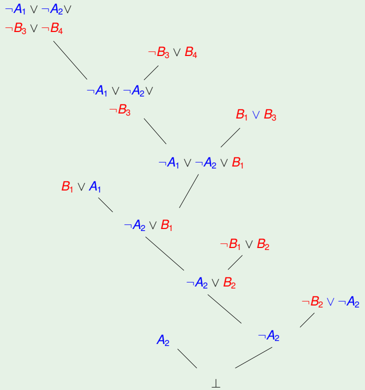
- optimized versions for the purely-propositional case [25, 27]

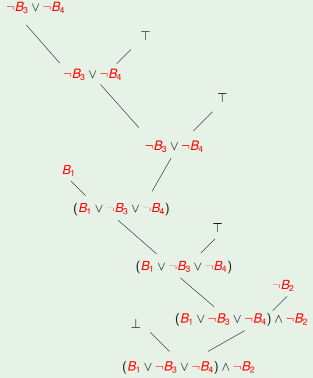
Computing Craig Interpolants in SAT: example

$$A \stackrel{\text{def}}{=} (B_1 \lor A_1) \land A_2 \land (\neg B_2 \lor \neg A_2) \land (\neg A_1 \lor \neg A_2 \lor \neg B_3 \lor \neg B_4)$$

$$B \stackrel{\text{def}}{=} (\neg B_3 \lor B_4) \land (\neg B_1 \lor B_2) \land (B_1 \lor B_3)$$



original proof



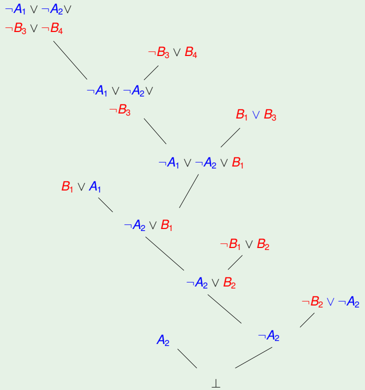
interpolant proof

$\Longrightarrow$ $(B_1 \lor \neg B_3 \lor \neg B_4) \land \neg B_2$ is an interpolant

Computing Craig Interpolants in SAT: example

$$A \stackrel{\text{def}}{=} (B_1 \vee A_1) \wedge A_2 \wedge (\neg B_2 \vee \neg A_2) \wedge (\neg A_1 \vee \neg A_2 \vee \neg B_3 \vee \neg B_4)$$

$$B \stackrel{\text{def}}{=} (\neg B_3 \vee B_4) \wedge (\neg B_1 \vee B_2) \wedge (B_1 \vee B_3)$$



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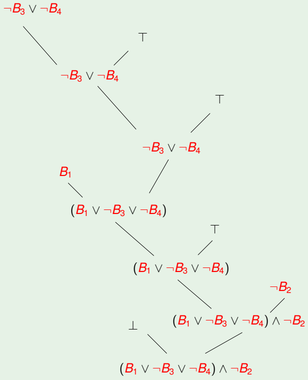

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MaxSAT (hints)

- MaxSAT: given a pair of CNF formulas $\langle \varphi_h, \varphi_s \rangle$ s.t. $\varphi_h \wedge \varphi_s \models \bot$, $\varphi_s \stackrel{\text{def}}{=} \{C_1, ..., C_k\}$, find a truth assignment μ satisfying φ_h and maximizing the amount of the satisfied clauses in φ_s.
- Weighted MaxSAT: given also the positive integer penalties $\{w_1, ..., w_k\}$, μ must satisfy φ_h and maximize the sum of penalties of the satisfied clauses in φ_s
- Generalization of SAT to optimization

  $\Longrightarrow$ much harder than SAT
- Many different approaches (see e.g. [22])
- EX:

$$\varphi_h \stackrel{\text{def}}{=} (A_1 \vee A_2) \qquad \varphi_s \stackrel{\text{def}}{=} \left(\begin{array}{cccc} (& A_1 \vee \neg A_2) & \wedge & [4] \\ (\neg A_1 \vee & A_2) & \wedge & [3] \\ (\neg A_1 \vee & \neg A_2) & \wedge & [2] \end{array} \right)$$

$\Longrightarrow \mu = \{A_1, A_2\}$ (penalty = 2)

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$\Longrightarrow \mu = \{A_1, A_2\}$ (penalty = 2)

All-SAT & Model Counting (hints)

- All-SAT: enumerate all truth assignments satisfying φ
  - a partial model μ not assigning k atoms represents 2^k models
- All-SAT over an "important" subset of atoms $\mathbf{P} \stackrel{\text{def}}{=} \{P_i\}_i$: enumerate all assignments over **P** which can be extended to satisfiable truth assignments propositionally satisfying φ
- Model Counting (aka #SAT) [17]: like All-SAT, but count models rathern than enumerate them.
  - a partial assignment μ not assigning k atoms is counted for 2^k

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The papers (co)authored by the author of these slides are availlable at:
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  `http://combination.cs.uiowa.edu/`
- The SAT Association
  `http://satassociation.org/`
- SATLive! - Up-to-date links for SAT
  `http://www.satlive.org/index.jsp`
- SATLIB - The Satisfiability Library
  `http://www.intellektik.informatik.tu-darmstadt.de/SATLIB/`