2.6 The CDCL Procedure

Goal:
Given a propositional formula in CNF (or alternatively, a finite set $N$ of clauses), check whether it is satisfiable (and optionally: output one solution, if it is satisfiable).

Assumption:
Clauses contain neither duplicated literals nor complementary literals.

CDCL: Conflict Driven Clause Learning

Satisfiability of Clause Sets

$\mathcal{A} \models N$ if and only if $\mathcal{A} \models C$ for all clauses $C$ in $N$.
$\mathcal{A} \models C$ if and only if $\mathcal{A} \models L$ for some literal $L \in C$.

Partial Valuations

Since we will construct satisfying valuations incrementally, we consider partial valuations (that is, partial mappings $\mathcal{A} : \Sigma \rightarrow \{0, 1\}$).

Every partial valuation $\mathcal{A}$ corresponds to a set $M$ of literals that does not contain complementary literals, and vice versa:

$\mathcal{A}(L)$ is true, if $L \in M$.
$\mathcal{A}(L)$ is false, if $\overline{L} \in M$.
$\mathcal{A}(L)$ is undefined, if neither $L \in M$ nor $\overline{L} \in M$.

We will use $\mathcal{A}$ and $M$ interchangeably. Note that truth of a literal with respect to $M$ is defined differently than for $N_I$.

A clause is true under a partial valuation $\mathcal{A}$ (or under a set $M$ of literals) if one of its literals is true; it is false (or “conflicting”) if all its literals are false; otherwise it is undefined (or “unresolved”).

37
Unit Clauses

Observation:
Let $A$ be a partial valuation. If the set $N$ contains a clause $C$, such that all literals but one in $C$ are false under $A$, then the following properties are equivalent:

- there is a valuation that is a model of $N$ and extends $A$.
- there is a valuation that is a model of $N$ and extends $A$ and makes the remaining literal $L$ of $C$ true.

$C$ is called a unit clause; $L$ is called a unit literal.

Pure Literals

One more observation:
Let $A$ be a partial valuation and $P$ a variable that is undefined under $A$. If $P$ occurs only positively (or only negatively) in the unresolved clauses in $N$, then the following properties are equivalent:

- there is a valuation that is a model of $N$ and extends $A$.
- there is a valuation that is a model of $N$ and extends $A$ and assigns 1 (0) to $P$.

$P$ is called a pure literal.

The Davis-Putnam-Logemann-Loveland Proc.

```plaintext
boolean DPLL(literal set $M$, clause set $N$) {
    if (all clauses in $N$ are true under $M$) return true;
    elsif (some clause in $N$ is false under $M$) return false;
    elsif ($N$ contains unit clause $P$) return DPLL($M \cup \{P\}$, $N$);
    elsif ($N$ contains unit clause $\neg P$) return DPLL($M \cup \{\neg P\}$, $N$);
    elsif ($N$ contains pure literal $P$) return DPLL($M \cup \{P\}$, $N$);
    elsif ($N$ contains pure literal $\neg P$) return DPLL($M \cup \{\neg P\}$, $N$);
    else {
        let $P$ be some undefined variable in $N$;
        if (DPLL($M \cup \{\neg P\}$, $N$)) return true;
        else return DPLL($M \cup \{P\}$, $N$);
    }
}
```

Initially, DPLL is called with an empty literal set and the clause set $N$. 


2.7 From DPLL to CDCL

In practice, there are several changes to the procedure:

The pure literal check is only done while preprocessing (otherwise is too expensive).

The branching variable is not chosen randomly.

The algorithm is implemented iteratively;
the backtrack stack is managed explicitly
(it may be possible and useful to backtrack more than one level).

CDCL = DPLL + Information is reused by learning + Restart + Specific Data Structures

Branching Heuristics

Choosing the right undefined variable to branch is important for efficiency, but the branching heuristics may be expensive itself.

State of the art: use branching heuristics that need not be recomputed too frequently.

In general: choose variables that occur frequently, prefer variables from recent conflicts.

The Deduction Algorithm

For applying the unit rule, we need to know the number of literals in a clause that are not false.

Maintaining this number is expensive, however.

Better approach: “Two watched literals”:

In each clause, select two (currently undefined) “watched” literals.

For each variable $P$, keep a list of all clauses in which $P$ is watched and a list of all clauses in which $\neg P$ is watched.

If an undefined variable is set to 0 (or to 1), check all clauses in which $P$ (or $\neg P$) is watched and watch another literal (that is true or undefined) in this clause if possible.

Watched literal information need not be restored upon backtracking.
Conflict Analysis and Learning

Goal: Reuse information that is obtained in one branch in further branches.

Method: Learning:

If a conflicting clause is found, derive a new clause from the conflict and add it to the current set of clauses.

Problem: This may produce a large number of new clauses; therefore it may become necessary to delete some of them afterwards to save space.

Backjumping

Related technique:
*non-chronological backtracking* ("backjumping"):

If a conflict is independent of some earlier branch, try to skip over that backtrack level.

Restart

Runtimes of DPLL-style procedures depend extremely on the choice of branching variables.

If no solution is found within a certain time limit, it can be useful to restart from scratch with an adopted variable selection heuristics, but learned clauses are kept.

In particular, after learning a unit clause a restart is done.

Formalizing DPLL with Refinements

The DPLL procedure is modelled by a transition relation \( \Rightarrow_{DPLL} \) on a set of states.

States:

- \( fail \)
- \((M; N)\)

where \( M \) is a list of annotated literals and \( N \) is a set of clauses. We use \(+\) to right add a literal or a list of literals to \( M \)

Annotated literal:

- \( L \): deduced literal, due to unit propagation.
- \( L^{d} \): decision literal (guessed literal).
Unit Propagate:

$$(M; N \cup \{C \lor L\}) \Rightarrow_{\text{DPLL}} (M + L; N \cup \{C \lor L\})$$

if $C$ is false under $M$ and $L$ is undefined under $M$.

Decide:

$$(M; N) \Rightarrow_{\text{DPLL}} (M + L^d; N)$$

if $L$ is undefined under $M$ and contained in $N$.

Fail:

$$(M; N \cup \{C\}) \Rightarrow_{\text{DPLL}} \text{fail}$$

if $C$ is false under $M$ and $M$ contains no decision literals.

Backjump:

$$(M' + L^d + M''; N) \Rightarrow_{\text{DPLL}} (M' + L'; N)$$

if there is some “backjump clause” $C \lor L'$ such that

$N \models C \lor L'$,

$C$ is false under $M'$, and

$L'$ is undefined under $M'$.

We will see later that the Backjump rule is always applicable, if the list of literals $M$ contains at least one decision literal and some clause in $N$ is false under $M$.

There are many possible backjump clauses. One candidate: $\bigvee_{i=1}^{n} L_i \lor \ldots \lor L_n$, where the $L_i$ are all the decision literals in $M + L^d + M'$. (But usually there are better choices.)

**Lemma 2.16** If we reach a state $(M; N)$ starting from $(\text{nil}; N)$, then:

1. $M$ does not contain complementary literals.
2. Every deduced literal $L$ in $M$ follows from $N$ and decision literals occurring before $L$ in $M$.

**Proof.** By induction on the length of the derivation. \hfill \Box

**Lemma 2.17** Every derivation starting from $(\text{nil}; N)$ terminates.

**Proof.** (Idea) Consider a DPLL derivation step $(M; N) \Rightarrow_{\text{DPLL}} (M'; N')$ and a decomposition $M_0 + L_1^d + M_1 + \ldots + L_k^d + M_k$ of $M$ (accordingly for $M'$). Let $n$ be the number of distinct propositional variables in $N$. Then $k$, $k'$ and the length of $M$, $M'$ are always smaller or equal to $n$. We define $f(M) = n - \text{length}(M)$ and finally

$$(M; N) \succ (M'; N') \quad \text{if}$$
Lemma 2.18 Suppose that we reach a state \((M; N)\) starting from \((\text{nil}; N)\) such that some clause \(D \in N\) is false under \(M\). Then:

(1) If \(M\) does not contain any decision literal, then “Fail” is applicable.

(2) Otherwise, “Backjump” is applicable.

Proof. (1) Obvious.

(2) Let \(L_1, \ldots, L_n\) be the decision literals occurring in \(M\) (in this order). Since \(M \models \neg D\), we obtain, by Lemma 2.16, \(N \cup \{L_1, \ldots, L_n\} \models \neg D\). Since \(D \in N\), this is a contradiction, so \(N \cup \{L_1, \ldots, L_n\}\) is unsatisfiable. Consequently, \(N \models \neg L_1 \lor \cdots \lor \neg L_n\). Now let \(C = \neg L_1 \lor \cdots \lor \neg L_{n-1}, L' = \neg L_n, L = L_n\), and let \(M'\) be the list of all literals of \(M\) occurring before \(L_n\), then the condition of “Backjump” is satisfied. \(\square\)

Theorem 2.19 (1) If we reach a final state \((M; N)\) starting from \((\text{nil}; N)\), then \(N\) is satisfiable and \(M\) is a model of \(N\).

(2) If we reach a final state fail starting from \((\text{nil}; N)\), then \(N\) is unsatisfiable.

Proof. (1) Observe that the “Decide” rule is applicable as long as literals are undefined under \(M\). Hence, in a final state, all literals must be defined. Furthermore, in a final state, no clause in \(N\) can be false under \(M\), otherwise “Fail” or “Backjump” would be applicable. Hence \(M\) is a model of every clause in \(N\).

(2) If we reach fail, then in the previous step we must have reached a state \((M; N)\) such that some \(C \in N\) is false under \(M\) and \(M\) contains no decision literals. By part (2) of Lemma 2.16, every literal in \(M\) follows from \(N\). On the other hand, \(C \in N\), so \(N\) must be unsatisfiable. \(\square\)

Getting Better Backjump Clauses

Suppose that we have reached a state \(M \parallel N\) such that some clause \(C \in N\) (or following from \(N\)) is false under \(M\).

Consequently, every literal of \(C\) is the complement of some literal in \(M\).

(1) If every literal in \(C\) is the complement of a decision literal of \(M\), then \(C\) is a backjump clause.