

Formalisation of Ground Resolution and CDCL in Isabelle/HOL

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February 4, 2016

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theory *Wellfounded-More*

imports *Main*

begin

1 Transitions

This theory contains more facts about closure, the definition of full transformations, and well-foundedness.

1.1 More theorems about Closures

This is the equivalent of $?r \leq ?s \implies ?r^{**} \leq ?s^{**}$ for *tranclp*

lemma *tranclp-mono-explicit*:

$r^{++} a b \implies r \leq s \implies s^{++} a b$

using *rtranclp-mono* **by** (*auto dest!*: *tranclpD intro: rtranclp-into-tranclp2*)

lemma *tranclp-mono*:

assumes *mono*: $r \leq s$

shows $r^{++} \leq s^{++}$

using *rtranclp-mono[OF mono]* *mono* **by** (*auto dest!*: *tranclpD intro: rtranclp-into-tranclp2*)

lemma *tranclp-idemp-rel*:

$R^{++++} a b \longleftrightarrow R^{++} a b$

apply (*rule iffI*)

prefer 2 **apply** *blast*

by (*induction rule: tranclp-induct*) *auto*

Equivalent of $?r^{****} = ?r^{**}$

lemma *trancl-idemp*: $(r^+)^+ = r^+$

by *simp*

lemmas *tranclp-idemp[simp]* = *trancl-idemp[to-pred]*

This theorem already exists as $?r^{**} ?a ?b \equiv ?a = ?b \vee ?r^{++} ?a ?b$ (and sledgehammer uses it), but it makes sense to duplicate it, because it is unclear how stable the lemmas in Nitpick are.

lemma *rtranclp-unfold*: $rtranclp r a b \longleftrightarrow (a = b \vee tranclp r a b)$

by (*meson rtranclp.simps rtranclpD tranclp-into-rtranclp*)

lemma *tranclp-unfold-end*: $tranclp r a b \longleftrightarrow (\exists a'. rtranclp r a a' \wedge r a' b)$

by (*metis rtranclp.rtrancl-refl rtranclp-into-tranclp1 tranclp.cases tranclp-into-rtranclp*)

lemma *tranclp-unfold-begin*: $tranclp r a b \longleftrightarrow (\exists a'. r a a' \wedge rtranclp r a' b)$

by (*meson rtranclp-into-tranclp2 tranclpD*)

lemma *trancl-set-tranclp*: $(a, b) \in \{(b, a). P a b\}^+ \longleftrightarrow P^{++} b a$

apply (*rule iffI*)

apply (*induction rule: trancl-induct; simp*)

apply (*induction rule: tranclp-induct; auto simp: trancl-into-trancl2*)

done

lemma *tranclp-rtranclp-rtranclp-rel*: $R^{++++} a b \longleftrightarrow R^{**} a b$

by (*simp add: rtranclp-unfold*)

lemma *tranclp-rtranclp-rtranclp[simp]*: $R^{++++} = R^{**}$

by (*fastforce simp: rtranclp-unfold*)

```

lemma rtranclp-exists-last-with-prop:
  assumes  $R\ x\ z$ 
  and  $R^{**}\ z\ z'$  and  $P\ x\ z$ 
  shows  $\exists y\ y'.\ R^{**}\ x\ y \wedge R\ y\ y' \wedge P\ y\ y' \wedge (\lambda a\ b.\ R\ a\ b \wedge \neg P\ a\ b)^{**}\ y'\ z'$ 
  using assms(2,1,3)
proof (induction arbitrary: )
  case base
  then show ?case by auto
next
  case (step  $z'\ z''$ ) note  $z = \text{this}(2)$  and  $IH = \text{this}(3)[OF\ \text{this}(4-5)]$ 
  show ?case
  apply (cases  $P\ z'\ z''$ )
  apply (rule exI[of -  $z'$ ], rule exI[of -  $z''$ ])
  using  $z\ \text{assms}(1)\ \text{step.hyps}(1)\ \text{step.prem}(2)$  apply auto[1]
  using  $IH\ z\ \text{rtranclp.rtrancl-into-rtrancl}$  by fastforce
qed

```

```

lemma rtranclp-and-rtranclp-left:  $(\lambda a\ b.\ P\ a\ b \wedge Q\ a\ b)^{**}\ S\ T \implies P^{**}\ S\ T$ 
by (induction rule: rtranclp-induct) auto

```

1.2 Full Transitions

We define here properties to define properties after all possible transitions.

abbreviation *no-step* $\text{step}\ S \equiv (\forall S'.\ \neg \text{step}\ S\ S')$

definition *full1* :: $('a \Rightarrow 'a \Rightarrow \text{bool}) \Rightarrow 'a \Rightarrow 'a \Rightarrow \text{bool}$ **where**
full1 transf = $(\lambda S\ S'.\ \text{trancpl transf}\ S\ S' \wedge (\forall S''.\ \neg \text{transf}\ S'\ S''))$

definition *full*:: $('a \Rightarrow 'a \Rightarrow \text{bool}) \Rightarrow 'a \Rightarrow 'a \Rightarrow \text{bool}$ **where**
full transf = $(\lambda S\ S'.\ \text{rtranclp transf}\ S\ S' \wedge (\forall S''.\ \neg \text{transf}\ S'\ S''))$

lemma *rtranclp-full1I*:
 $R^{**}\ a\ b \implies \text{full1}\ R\ b\ c \implies \text{full1}\ R\ a\ c$
unfolding *full1-def* **by** *auto*

lemma *trancpl-full1I*:
 $R^{++}\ a\ b \implies \text{full1}\ R\ b\ c \implies \text{full1}\ R\ a\ c$
unfolding *full1-def* **by** *auto*

lemma *rtranclp-fullI*:
 $R^{**}\ a\ b \implies \text{full}\ R\ b\ c \implies \text{full}\ R\ a\ c$
unfolding *full-def* **by** *auto*

lemma *trancpl-full-full1I*:
 $R^{++}\ a\ b \implies \text{full}\ R\ b\ c \implies \text{full1}\ R\ a\ c$
unfolding *full-def full1-def* **by** *auto*

lemma *full-fullI*:
 $R\ a\ b \implies \text{full}\ R\ b\ c \implies \text{full1}\ R\ a\ c$
unfolding *full-def full1-def* **by** *auto*

lemma *full-unfold*:
 $\text{full}\ r\ S\ S' \longleftrightarrow ((S = S' \wedge \text{no-step}\ r\ S') \vee \text{full1}\ r\ S\ S')$
unfolding *full-def full1-def* **by** (*auto simp add: rtranclp-unfold*)

lemma *full1-is-full[intro]*: $full1\ R\ S\ T \implies full\ R\ S\ T$
 by (*simp add: full-unfold*)

lemma *not-full1-rtranclp-relation*: $\neg full1\ R^{**}\ a\ b$
 by (*meson full1-def rtranclp.rtrancl-refl*)

lemma *not-full-rtranclp-relation*: $\neg full\ R^{**}\ a\ b$
 by (*meson full-fullI not-full1-rtranclp-relation rtranclp.rtrancl-refl*)

lemma *full1-tranclp-relation-full*:
 $full1\ R^{++}\ a\ b \longleftrightarrow full1\ R\ a\ b$
 by (*metis converse-tranclpE full1-def reflclp-tranclp rtranclpD rtranclp-idemp rtranclp-reflclp tranclp.r-into-trancl tranclp-into-rtranclp*)

lemma *full-tranclp-relation-full*:
 $full\ R^{++}\ a\ b \longleftrightarrow full\ R\ a\ b$
 by (*metis full-unfold full1-tranclp-relation-full tranclp.r-into-trancl tranclpD*)

lemma *rtranclp-full1-eq-or-full1*:
 $(full1\ R)^{**}\ a\ b \longleftrightarrow (a = b \vee full1\ R\ a\ b)$
proof –
 have $\forall p\ a\ aa.\ \neg p^{**}\ (a::'a)\ aa \vee a = aa \vee (\exists ab.\ p^{**}\ a\ ab \wedge p\ ab\ aa)$
 by (*metis rtranclp.cases*)
 then obtain $aa :: ('a \Rightarrow 'a \Rightarrow bool) \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a$ **where**
 $f1: \forall p\ a\ ab.\ \neg p^{**}\ a\ ab \vee a = ab \vee p^{**}\ a\ (aa\ p\ a\ ab) \wedge p\ (aa\ p\ a\ ab)\ ab$
 by *moura*
 { **assume** $a \neq b$
 { **assume** $\neg full1\ R\ a\ b \wedge a \neq b$
 then have $a \neq b \wedge a \neq b \wedge \neg full1\ R\ (aa\ (full1\ R)\ a\ b)\ b \vee \neg (full1\ R)^{**}\ a\ b \wedge a \neq b$
 using $f1$ by (*metis (no-types) full1-def full1-tranclp-relation-full*)
 then have *?thesis*
 using $f1$ by *blast* }
 then have *?thesis*
 by *auto* }
 then show *?thesis*
 by *fastforce*
qed

lemma *tranclp-full1-full1*:
 $(full1\ R)^{++}\ a\ b \longleftrightarrow full1\ R\ a\ b$
 by (*metis full1-def rtranclp-full1-eq-or-full1 tranclp-unfold-begin*)

1.3 Well-Foundedness and Full Transitions

lemma *wf-exists-normal-form*:
assumes $wf:wf\ \{(x, y).\ R\ y\ x\}$
shows $\exists b.\ R^{**}\ a\ b \wedge no\text{-}step\ R\ b$
proof (*rule ccontr*)
assume $\neg ?thesis$
 then have $H: \bigwedge b.\ \neg R^{**}\ a\ b \vee \neg no\text{-}step\ R\ b$
 by *blast*
 def $F \equiv rec\text{-}nat\ a\ (\lambda i\ b.\ SOME\ c.\ R\ b\ c)$
 have [*simp*]: $F\ 0 = a$
 unfolding *F-def* by *auto*
 have [*simp*]: $\bigwedge i.\ F\ (Suc\ i) = (SOME\ b.\ R\ (F\ i)\ b)$
 using *F-def* by *simp*

```

{ fix i
  have  $\forall j < i. R (F j) (F (Suc j))$ 
  proof (induction i)
    case 0
    then show ?case by auto
  next
    case (Suc i)
    then have  $R^{**} a (F i)$ 
    by (induction i) auto
    then have  $R (F i) (SOME b. R (F i) b)$ 
    using H by (simp add: someI-ex)
    then have  $\forall j < Suc i. R (F j) (F (Suc j))$ 
    using H Suc by (simp add: less-Suc-eq)
    then show ?case by fast
  qed
}
then have  $\forall j. R (F j) (F (Suc j))$  by blast
then show False
  using wf unfolding wfP-def wf-iff-no-infinite-down-chain by blast
qed

```

```

lemma wf-exists-normal-form-full:
  assumes wf:wf  $\{(x, y). R y x\}$ 
  shows  $\exists b. full R a b$ 
  using wf-exists-normal-form[OF assms] unfolding full-def by blast

```

1.4 More Well-Foundedness

A little list of theorems that could be useful, but are hidden:

- link between wf and infinite chains: $wf ?r = (\neg (\exists f. \forall i. (f (Suc i), f i) \in ?r)), \llbracket wf ?r; \bigwedge k. (?f (Suc k), ?f k) \notin ?r \implies ?thesis \rrbracket \implies ?thesis$

```

lemma wf-if-measure-in-wf:
  wf R  $\implies (\bigwedge a b. (a, b) \in S \implies (\nu a, \nu b) \in R) \implies wf S$ 
  by (metis in-inv-image wfE-min wfI-min wf-inv-image)

```

```

lemma wfP-if-measure: fixes f :: 'a  $\Rightarrow$  nat
shows  $(\bigwedge x y. P x \implies g x y \implies f y < f x) \implies wf \{(y, x). P x \wedge g x y\}$ 
  apply (insert wf-measure[of f])
  apply (simp only: measure-def inv-image-def less-than-def less-eq)
  apply (erule wf-subset)
  apply auto
done

```

```

lemma wf-if-measure-f:
  assumes wf r
  shows wf  $\{(b, a). (f b, f a) \in r\}$ 
  using assms by (metis inv-image-def wf-inv-image)

```

```

lemma wf-wf-if-measure':
  assumes wf r and H:  $(\bigwedge x y. P x \implies g x y \implies (f y, f x) \in r)$ 
  shows wf  $\{(y, x). P x \wedge g x y\}$ 
  proof -
    have wf  $\{(b, a). (f b, f a) \in r\}$  using assms(1) wf-if-measure-f by auto

```


then have $wf \{(b, a). P a \wedge g a b \wedge (f b, f a) \in r\}$
 using $wf\text{-subset}[of - \{(b, a). P a \wedge g a b \wedge (f b, f a) \in r\}]$ **by** *auto*
 moreover have $\{(b, a). P a \wedge g a b \wedge (f b, f a) \in r\} \subseteq \{(b, a). (f b, f a) \in r\}$ **by** *auto*
 moreover have $\{(b, a). P a \wedge g a b \wedge (f b, f a) \in r\} = \{(b, a). P a \wedge g a b\}$ **using** H **by** *auto*
 ultimately show *?thesis* **using** $wf\text{-subset}$ **by** *simp*
qed

lemma *wf-lex-less*: $wf (lex \{(a, b). (a::nat) < b\})$
proof –
 have $m: \{(a, b). a < b\} = \text{measure id}$ **by** *auto*
 show *?thesis* **apply** (*rule wf-lex*) **unfolding** m **by** *auto*
qed

lemma *wfP-if-measure2*: **fixes** $f :: 'a \Rightarrow nat$
shows $(\bigwedge x y. P x y \Longrightarrow g x y \Longrightarrow f x < f y) \Longrightarrow wf \{(x, y). P x y \wedge g x y\}$
apply(*insert wf-measure[of f]*)
apply(*simp only: measure-def inv-image-def less-than-def less-eq*)
apply(*erule wf-subset*)
apply *auto*
done

lemma *lexord-on-finite-set-is-wf*:
assumes
 $P\text{-finite}: \bigwedge U. P U \longrightarrow U \in A$ **and**
 $finite: finite A$ **and**
 $wf: wf R$ **and**
 $trans: trans R$
shows $wf \{(T, S). (P S \wedge P T) \wedge (T, S) \in lexord R\}$
proof (*rule wfP-if-measure2*)
fix $T S$
assume $P: P S \wedge P T$ **and**
 $s\text{-le-}t: (T, S) \in lexord R$
let $?f = \lambda S. \{U. (U, S) \in lexord R \wedge P U \wedge P S\}$
have $?f T \subseteq ?f S$
 using $s\text{-le-}t P lexord\text{-}trans trans$ **by** *auto*
moreover **have** $T \in ?f S$
 using $s\text{-le-}t P$ **by** *auto*
moreover **have** $T \notin ?f T$
 using $s\text{-le-}t$ **by** (*auto simp add: lexord-irreflexive local.wf*)
ultimately **have** $\{U. (U, T) \in lexord R \wedge P U \wedge P T\} \subset \{U. (U, S) \in lexord R \wedge P U \wedge P S\}$
by *auto*
moreover **have** $finite \{U. (U, S) \in lexord R \wedge P U \wedge P S\}$
 using $finite$ **by** (*metis (no-types, lifting) P-finite finite-subset mem-Collect-eq subsetI*)
ultimately **show** $card (?f T) < card (?f S)$ **by** (*simp add: psubset-card-mono*)
qed

lemma *wf-fst-wf-pair*:
assumes $wf \{(M', M). R M' M\}$
shows $wf \{((M', N'), (M, N)). R M' M\}$
proof –
have $wf (\{(M', M). R M' M\} <*\text{lex}*> \{\})$
 using *assms* **by** *auto*
then show *?thesis*
by (*rule wf-subset*) *auto*

qed

lemma *wf-snd-wf-pair*:

assumes *wf* $\{(M', M). R M' M\}$
 shows *wf* $\{((M', N'), (M, N)). R N' N\}$

proof –

have *wf*: *wf* $\{((M', N'), (M, N)). R M' M\}$

using *assms wf-fst-wf-pair* by *auto*

then have *wf*: $\bigwedge P. (\forall x. (\forall y. (y, x) \in \{((M', N'), M, N). R M' M\} \longrightarrow P y) \longrightarrow P x) \implies \text{All } P$
 unfolding *wf-def* by *auto*

show *?thesis*

unfolding *wf-def*

proof (*intro allI impI*)

fix *P* :: $'c \times 'a \Rightarrow \text{bool}$ and *x* :: $'c \times 'a$

assume *H*: $\forall x. (\forall y. (y, x) \in \{((M', N'), M, y). R N' y\} \longrightarrow P y) \longrightarrow P x$

obtain *a b* where *x*: $x = (a, b)$ by (*cases x*)

have *P*: $P x = (P \circ (\lambda(a, b). (b, a))) (b, a)$

unfolding *x* by *auto*

show *P x*

using *wf*[*of P o* ($\lambda(a, b). (b, a)$)] apply *rule*

using *H* apply *simp*

unfolding *P* by *blast*

qed

qed

lemma *wf-if-measure-f-notation2*:

assumes *wf r*

shows *wf* $\{(b, h a)|b a. (f b, f (h a)) \in r\}$

apply (*rule wf-subset*)

using *wf-if-measure-f*[*OF assms, of f*] by *auto*

lemma *wf-wf-if-measure'-notation2*:

assumes *wf r* and *H*: $(\bigwedge x y. P x \implies g x y \implies (f y, f (h x)) \in r)$

shows *wf* $\{(y, h x)| y x. P x \wedge g x y\}$

proof –

have *wf* $\{(b, h a)|b a. (f b, f (h a)) \in r\}$ using *assms(1) wf-if-measure-f-notation2* by *auto*

then have *wf* $\{(b, h a)|b a. P a \wedge g a b \wedge (f b, f (h a)) \in r\}$

using *wf-subset*[*of -* $\{(b, h a)|b a. P a \wedge g a b \wedge (f b, f (h a)) \in r\}$] by *auto*

moreover have $\{(b, h a)|b a. P a \wedge g a b \wedge (f b, f (h a)) \in r\}$

$\subseteq \{(b, h a)|b a. (f b, f (h a)) \in r\}$ by *auto*

moreover have $\{(b, h a)|b a. P a \wedge g a b \wedge (f b, f (h a)) \in r\} = \{(b, h a)|b a. P a \wedge g a b\}$

using *H* by *auto*

ultimately show *?thesis* using *wf-subset* by *simp*

qed

end

theory *List-More*

imports *Main*

begin

2 Various Lemmas

Close to $(\bigwedge n. \forall m < n. ?P m \implies ?P n) \implies ?P ?n$, but with a separation between zero and non-zero, and case names.

```

thm nat-less-induct
lemma nat-less-induct-case[case-names 0 Suc]:
  assumes
     $P\ 0$  and
     $\bigwedge n. (\forall m < \text{Suc } n. P\ m) \implies P\ (\text{Suc } n)$ 
  shows  $P\ n$ 
  apply (induction rule: nat-less-induct)
  by (case-tac n) (auto intro: assms)

```

This is only proved in simple cases by auto. In assumptions, nothing happens, and $?P$ (if $?Q$ then $?x$ else $?y$) = $(\neg (?Q \wedge \neg ?P\ ?x \vee \neg ?Q \wedge \neg ?P\ ?y))$ can blow up goals (because of other if expression).

```

lemma if-0-1-ge-0[simp]:
   $0 < (\text{if } P \text{ then } a \text{ else } (0::\text{nat})) \longleftrightarrow P \wedge 0 < a$ 
  by auto

```

Bounded function have not been defined in Isabelle.

```

definition bounded where
  bounded  $f \longleftrightarrow (\exists b. \forall n. f\ n \leq b)$ 

```

```

abbreviation unbounded :: ('a  $\Rightarrow$  'b::ord)  $\Rightarrow$  bool where
  unbounded  $f \equiv \neg$  bounded  $f$ 

```

```

lemma not-bounded-nat-exists-larger:
  fixes  $f :: \text{nat} \Rightarrow \text{nat}$ 
  assumes unbound: unbounded  $f$ 
  shows  $\exists n. f\ n > m \wedge n > n_0$ 
proof (rule ccontr)
  assume  $H: \neg ?thesis$ 
  have finite { $f\ n \mid n. n \leq n_0$ }
  by auto
  have  $\bigwedge n. f\ n \leq \text{Max } (\{f\ n \mid n. n \leq n_0\} \cup \{m\})$ 
  apply (case-tac  $n \leq n_0$ )
  apply (metis (mono-tags, lifting) Max-ge Un-insert-right {finite { $f\ n \mid n. n \leq n_0$ }}
    finite-insert insertCI mem-Collect-eq sup-bot.right-neutral)
  by (metis (no-types, lifting)  $H$  Max-less-iff Un-insert-right {finite { $f\ n \mid n. n \leq n_0$ }}
    finite-insert insertI1 insert-not-empty leI sup-bot.right-neutral)
  then show False
  using unbound unfolding bounded-def by auto
qed

```

```

lemma bounded-const-product:
  fixes  $k :: \text{nat}$  and  $f :: \text{nat} \Rightarrow \text{nat}$ 
  assumes  $k > 0$ 
  shows bounded  $f \longleftrightarrow$  bounded  $(\lambda i. k * f\ i)$ 
  unfolding bounded-def apply (rule iffI)
  using mult-le-mono2 apply blast
  by (meson assms le-less-trans less-or-eq-imp-le nat-mult-less-cancel-disj split-div-lemma)

```

This lemma is not used, but here to show that a property that can be expected from *bounded* holds.

```

lemma bounded-finite-linorder:
  fixes  $f :: 'a \Rightarrow 'a :: \{\text{finite}, \text{linorder}\}$ 
  shows bounded  $f$ 
proof –

```

```

have  $\bigwedge x. f\ x \leq \text{Max}\ \{f\ x \mid x. \text{True}\}$ 
  by (metis (mono-tags) Max-ge finite mem-Collect-eq)
then show ?thesis
  unfolding bounded-def by blast
qed

```

3 More List

3.1 *upt*

The simplification rules are not very handy, because $[?i..<\text{Suc}\ ?j] = (\text{if } ?i \leq ?j \text{ then } [?i..<?j] @ [?j] \text{ else } [])$ leads to a case distinction, that we do not want if the condition is not in the context.

```

lemma upt-Suc-le-append:  $\neg i \leq j \implies [i..<\text{Suc}\ j] = []$ 
  by auto

```

```

lemmas upt-simps[simp] = upt-Suc-append upt-Suc-le-append

```

```

declare upt.simps(2)[simp del]

```

```

lemma
  assumes  $i \leq n - m$ 
  shows  $\text{take}\ i\ [m..<n] = [m..<m+i]$ 
  by (metis Nat.le-diff-conv2 add.commute assms diff-is-0-eq' linear take-upt upt-conv-Nil)

```

The counterpart for this lemma when $n - m < i$ is $\text{length}\ ?xs \leq ?n \implies \text{take}\ ?n\ ?xs = ?xs$. It is close to $?i + ?m \leq ?n \implies \text{take}\ ?m\ [?i..<?n] = [?i..<?i + ?m]$, but seems more general.

```

lemma take-upt-bound-minus[simp]:
  assumes  $i \leq n - m$ 
  shows  $\text{take}\ i\ [m..<n] = [m..<m+i]$ 
  using assms by (induction i) auto

```

```

lemma append-cons-eq-upt:
  assumes  $A @ B = [m..<n]$ 
  shows  $A = [m..<m+\text{length}\ A]$  and  $B = [m + \text{length}\ A..<n]$ 
proof -
  have  $\text{take}\ (\text{length}\ A)\ (A @ B) = A$  by auto
  moreover
    have  $\text{length}\ A \leq n - m$  using assms linear calculation by fastforce
    then have  $\text{take}\ (\text{length}\ A)\ [m..<n] = [m..<m+\text{length}\ A]$  by auto
  ultimately show  $A = [m..<m+\text{length}\ A]$  using assms by auto
  show  $B = [m + \text{length}\ A..<n]$  using assms by (metis append-eq-conv-conj drop-upt)
qed

```

The converse of $?A @ ?B = [?m..<?n] \implies ?A = [?m..<?m + \text{length}\ ?A]$
 $?A @ ?B = [?m..<?n] \implies ?B = [?m + \text{length}\ ?A..<?n]$ does not hold, for example if B is empty and A is $[0::'a]$:

```

lemma  $A @ B = [m..<n] \longleftrightarrow A = [m..<m+\text{length}\ A] \wedge B = [m + \text{length}\ A..<n]$ 

```

oops

A more restrictive version holds:

lemma $B \neq [] \implies A @ B = [m..<n] \longleftrightarrow A = [m..<m+\text{length } A] \wedge B = [m + \text{length } A..<n]$
 (is $?P \implies ?A = ?B$)

proof

assume $?A$ then show $?B$ by (auto simp add: append-cons-eq-upt)

next

assume $?P$ and $?B$

then show $?A$ using append-eq-conv-conj by fastforce

qed

lemma append-cons-eq-upt-length-i:

assumes $A @ i \# B = [m..<n]$

shows $A = [m..<i]$

proof -

have $A = [m..<m + \text{length } A]$ using assms append-cons-eq-upt by auto

have $(A @ i \# B) ! (\text{length } A) = i$ by auto

moreover have $n - m = \text{length } (A @ i \# B)$

using assms length-upt by presburger

then have $[m..<n] ! (\text{length } A) = m + \text{length } A$ by simp

ultimately have $i = m + \text{length } A$ using assms by auto

then show $?thesis$ using $\langle A = [m..<m + \text{length } A] \rangle$ by auto

qed

lemma append-cons-eq-upt-length:

assumes $A @ i \# B = [m..<n]$

shows $\text{length } A = i - m$

using assms

proof (induction A arbitrary: m)

case Nil

then show $?case$ by (metis append-Nil diff-is-0-eq list.size(3) order-refl upt-eq-Cons-conv)

next

case (Cons a A)

then have $A: A @ i \# B = [m + 1..<n]$ by (metis append-Cons upt-eq-Cons-conv)

then have $m < i$ by (metis Cons.premis append-cons-eq-upt-length-i upt-eq-Cons-conv)

with Cons.IH[OF A] show $?case$ by auto

qed

lemma append-cons-eq-upt-length-i-end:

assumes $A @ i \# B = [m..<n]$

shows $B = [\text{Suc } i..<n]$

proof -

have $B = [\text{Suc } m + \text{length } A..<n]$ using assms append-cons-eq-upt[of A @ [i] B m n] by auto

have $(A @ i \# B) ! (\text{length } A) = i$ by auto

moreover have $n - m = \text{length } (A @ i \# B)$

using assms length-upt by auto

then have $[m..<n] ! (\text{length } A) = m + \text{length } A$ by simp

ultimately have $i = m + \text{length } A$ using assms by auto

then show $?thesis$ using $\langle B = [\text{Suc } m + \text{length } A..<n] \rangle$ by auto

qed

lemma Max-n-upt: $\text{Max } (\text{insert } 0 \{ \text{Suc } 0..<n \}) = n - \text{Suc } 0$

proof (induct n)

case 0

then show $?case$ by simp

next

case (Suc n) note IH = this

```

have i: insert 0 {Suc 0..Suc n} = insert 0 {Suc 0..n} ∪ {n} by auto
show ?case using IH unfolding i by auto
qed

```

lemma *upt-decomp-lt*:

```

assumes H: xs @ i # ys @ j # zs = [m..n]
shows i < j

```

proof –

```

have xs: xs = [m..i] and ys: ys = [Suc i..j] and zs: zs = [Suc j..n]
using H by (auto dest: append-cons-eq-upt-length-i append-cons-eq-upt-length-i-end)
show ?thesis
by (metis append-cons-eq-upt-length-i-end assms lessI less-trans self-append-conv2
    upt-eq-Cons-conv upt-rec ys)

```

qed

3.2 Lexicographic ordering

We are working a lot on lexicographic ordering over pairs.

lemma *list-length2-append-cons*:

```

[c, d] = ys @ y # ys' ⟷ (ys = [] ∧ y = c ∧ ys' = [d]) ∨ (ys = [c] ∧ y = d ∧ ys' = [])
by (cases ys; cases ys') auto

```

lemma *lexn2-conv*:

```

([a, b], [c, d]) ∈ lexn r 2 ⟷ (a, c) ∈ r ∨ (a = c ∧ (b, d) ∈ r)
unfolding lexn-conv by (auto simp add: list-length2-append-cons)

```

end

theory *Prop-Logic*

imports *Main*

begin

4 Logics

In this section we define the syntax of the formula and an abstraction over it to have simpler proofs. After that we define some properties like subformula and rewriting.

4.1 Definition and abstraction

The propositional logic is defined inductively. The type parameter is the type of the variables.

datatype *'v propo* =

```

FT | FF | FVar 'v | FNot 'v propo | FAnd 'v propo 'v propo | FOR 'v propo 'v propo
| FImp 'v propo 'v propo | FEq 'v propo 'v propo

```

We do not define any notation for the formula, to distinguish properly between the formulas and Isabelle's logic.

To ease the proofs, we will write the the formula on a homogeneous manner, namely a connecting argument and a list of arguments.

datatype *'v connective* = *CT* | *CF* | *CVar* *'v* | *CNot* | *CAnd* | *COr* | *CImp* | *CEq*

abbreviation *nullary-connective* $\equiv \{CF\} \cup \{CT\} \cup \{CVar\ x \mid x. True\}$

definition *binary-connectives* $\equiv \{CAnd, COr, CImp, CEq\}$

We define our own induction principal: instead of distinguishing every constructor, we group them by arity.

lemma *propo-induct-arity*[*case-names nullary unary binary*]:

fixes $\varphi\ \psi :: 'v\ propo$
assumes *nullary*: $(\bigwedge \varphi\ x. \varphi = FF \vee \varphi = FT \vee \varphi = FVar\ x \implies P\ \varphi)$
and *unary*: $(\bigwedge \psi. P\ \psi \implies P\ (FNot\ \psi))$
and *binary*: $(\bigwedge \varphi\ \psi1\ \psi2. P\ \psi1 \implies P\ \psi2 \implies \varphi = FAnd\ \psi1\ \psi2 \vee \varphi = FOr\ \psi1\ \psi2 \vee \varphi = FImp\ \psi1\ \psi2 \vee \varphi = FEq\ \psi1\ \psi2 \implies P\ \varphi)$
shows $P\ \psi$
apply (*induct rule: propo.induct*)
using *assms by metis+*

The function *conn* is the interpretation of our representation (connective and list of arguments). We define any thing that has no sense to be false

fun *conn* :: $'v\ connective \Rightarrow 'v\ propo\ list \Rightarrow 'v\ propo$ **where**

conn *CT* [] = *FT* |
conn *CF* [] = *FF* |
conn (*CVar* *v*) [] = *FVar* *v* |
conn *CNot* [φ] = *FNot* φ |
conn *CAnd* ($\varphi \# [\psi]$) = *FAnd* $\varphi\ \psi$ |
conn *COr* ($\varphi \# [\psi]$) = *FOr* $\varphi\ \psi$ |
conn *CImp* ($\varphi \# [\psi]$) = *FImp* $\varphi\ \psi$ |
conn *CEq* ($\varphi \# [\psi]$) = *FEq* $\varphi\ \psi$ |
conn - - = *FF*

We will often use case distinction, based on the arity of the *'v connective*, thus we define our own splitting principle.

lemma *connective-cases-arity*:

assumes *nullary*: $\bigwedge x. c = CT \vee c = CF \vee c = CVar\ x \implies P$
and *binary*: $c \in \text{binary-connectives} \implies P$
and *unary*: $c = CNot \implies P$
shows P
using *assms by (case-tac c, auto simp add: binary-connectives-def)*

lemma *connective-cases-arity-2*[*case-names nullary unary binary*]:

assumes *nullary*: $c \in \text{nullary-connective} \implies P$
and *unary*: $c = CNot \implies P$
and *binary*: $c \in \text{binary-connectives} \implies P$
shows P
using *assms by (case-tac c, auto simp add: binary-connectives-def)*

Our previous definition is not necessary correct (connective and list of arguments) , so we define an inductive predicate.

inductive *wf-conn* :: $'v\ connective \Rightarrow 'v\ propo\ list \Rightarrow bool$ **for** $c :: 'v\ connective$ **where**

wf-conn-nullary[*simp*]: $(c = CT \vee c = CF \vee c = CVar\ v) \implies wf-conn\ c\ []$ |

wf-conn-unary[*simp*]: $c = CNot \implies wf-conn\ c\ [\psi]$ |

wf-conn-binary[*simp*]: $c \in \text{binary-connectives} \implies wf-conn\ c\ (\psi \# \psi' \# [])$

thm *wf-conn.induct*

lemma *wf-conn-induct*[*consumes 1, case-names CT CF CVar CNot COr CAnd CImp CEq*]:

assumes *wf-conn c x* **and**
 $(\bigwedge v. c = CT \implies P \ [])$ **and**
 $(\bigwedge v. c = CF \implies P \ [])$ **and**
 $(\bigwedge v. c = CVar\ v \implies P \ [])$ **and**
 $(\bigwedge \psi. c = CNot \implies P \ [\psi])$ **and**
 $(\bigwedge \psi\ \psi'. c = COr \implies P \ [\psi, \psi'])$ **and**
 $(\bigwedge \psi\ \psi'. c = CAnd \implies P \ [\psi, \psi'])$ **and**
 $(\bigwedge \psi\ \psi'. c = CImp \implies P \ [\psi, \psi'])$ **and**
 $(\bigwedge \psi\ \psi'. c = CEq \implies P \ [\psi, \psi'])$
shows $P\ x$
using *assms* **by** *induction (auto simp add: binary-connectives-def)*

4.2 properties of the abstraction

First we can define simplification rules.

lemma *wf-conn-conn[simp]*:
 $wf-conn\ CT\ l \implies conn\ CT\ l = FT$
 $wf-conn\ CF\ l \implies conn\ CF\ l = FF$
 $wf-conn\ (CVar\ x)\ l \implies conn\ (CVar\ x)\ l = FVar\ x$
apply (*simp-all add: wf-conn.simps*)
unfolding *binary-connectives-def* **by** *simp-all*

lemma *wf-conn-list-decomp[simp]*:
 $wf-conn\ CT\ l \longleftrightarrow l = []$
 $wf-conn\ CF\ l \longleftrightarrow l = []$
 $wf-conn\ (CVar\ x)\ l \longleftrightarrow l = []$
 $wf-conn\ CNot\ (\xi\ @\ \varphi\ \#\ \xi') \longleftrightarrow \xi = [] \wedge \xi' = []$
apply (*simp-all add: wf-conn.simps*)
unfolding *binary-connectives-def* **apply** *simp-all*
by (*metis append-Nil append-is-Nil-conv list.distinct(1) list.sel(3) tl-append2*)

lemma *wf-conn-list*:
 $wf-conn\ c\ l \implies conn\ c\ l = FT \longleftrightarrow (c = CT \wedge l = [])$
 $wf-conn\ c\ l \implies conn\ c\ l = FF \longleftrightarrow (c = CF \wedge l = [])$
 $wf-conn\ c\ l \implies conn\ c\ l = FVar\ x \longleftrightarrow (c = CVar\ x \wedge l = [])$
 $wf-conn\ c\ l \implies conn\ c\ l = FAnd\ a\ b \longleftrightarrow (c = CAnd \wedge l = a\ \#\ b\ \# [])$
 $wf-conn\ c\ l \implies conn\ c\ l = FOr\ a\ b \longleftrightarrow (c = COr \wedge l = a\ \#\ b\ \# [])$
 $wf-conn\ c\ l \implies conn\ c\ l = FEq\ a\ b \longleftrightarrow (c = CEq \wedge l = a\ \#\ b\ \# [])$
 $wf-conn\ c\ l \implies conn\ c\ l = FImp\ a\ b \longleftrightarrow (c = CImp \wedge l = a\ \#\ b\ \# [])$
 $wf-conn\ c\ l \implies conn\ c\ l = FNot\ a \longleftrightarrow (c = CNot \wedge l = a\ \# [])$
apply (*induct l rule: wf-conn.induct*)
unfolding *binary-connectives-def* **by** *auto*

In the binary connective cases, we will often decompose the list of arguments (of length 2) into two elements.

lemma *list-length2-decomp*: $length\ l = 2 \implies (\exists\ a\ b. l = a\ \#\ b\ \# [])$
apply (*induct l, auto*)
by (*case-tac l, auto*)

wf-conn for binary operators means that there are two arguments.

lemma *wf-conn-bin-list-length*:
fixes $l :: 'v\ propo\ list$


```

assumes conn:  $c \in \text{binary-connectives}$ 
shows  $\text{length } l = 2 \longleftrightarrow \text{wf-conn } c \ l$ 
proof
  assume  $\text{length } l = 2$ 
  thus  $\text{wf-conn } c \ l$  using wf-conn-binary list-length2-decomp using conn by metis
next
  assume  $\text{wf-conn } c \ l$ 
  thus  $\text{length } l = 2$  (is ?P l)
  proof (cases rule: wf-conn.induct)
    case wf-conn-nullary
    thus ?P [] using conn binary-connectives-def
    using connective.distinct(11) connective.distinct(13) connective.distinct(9) by blast
  next
    fix  $\psi :: 'v \text{ propo}$ 
    case wf-conn-unary
    thus ?P [ $\psi$ ] using conn binary-connectives-def
    using connective.distinct by blast
  next
    fix  $\psi \ \psi' :: 'v \text{ propo}$ 
    show ?P [ $\psi, \psi'$ ] by auto
  qed
qed

lemma wf-conn-not-list-length[iff]:
  fixes  $l :: 'v \text{ propo list}$ 
  shows  $\text{wf-conn } CNot \ l \longleftrightarrow \text{length } l = 1$ 
  apply auto
  apply (metis append-Nil connective.distinct(5,17,27) length-Cons list.size(3) wf-conn.simps
    wf-conn-list-decomp(4))
  by (simp add: length-Suc-conv wf-conn.simps)

```

Decomposing the Not into an element is moreover very useful.

```

lemma wf-conn-Not-decomp:
  fixes  $l :: 'v \text{ propo list}$  and  $a :: 'v$ 
  assumes corr:  $\text{wf-conn } CNot \ l$ 
  shows  $\exists a. l = [a]$ 
  by (metis (no-types, lifting) One-nat-def Suc-length-conv corr length-0-conv wf-conn-not-list-length)

```

The *wf-conn* remains correct if the length of list does not change. This lemma is very useful when we do one rewriting step

```

lemma wf-conn-no-arity-change:
   $\text{length } l = \text{length } l' \implies \text{wf-conn } c \ l \longleftrightarrow \text{wf-conn } c \ l'$ 
proof –
  {
    fix  $l \ l'$ 
    have  $\text{length } l = \text{length } l' \implies \text{wf-conn } c \ l \implies \text{wf-conn } c \ l'$ 
    apply (cases c l rule: wf-conn.induct, auto)
    by (metis wf-conn-bin-list-length)
  }
  thus  $\text{length } l = \text{length } l' \implies \text{wf-conn } c \ l = \text{wf-conn } c \ l'$  by metis
qed

```

```

lemma wf-conn-no-arity-change-helper:
   $\text{length } (\xi @ \varphi \# \xi') = \text{length } (\xi @ \varphi' \# \xi')$ 
by auto

```

The injectivity of *conn* is useful to prove equality of the connectives and the lists.

lemma *conn-inj-not*:

```

assumes correct: wf-conn c l
and conn: conn c l = FNot  $\psi$ 
shows c = CNot and l = [ $\psi$ ]
apply (cases c l rule: wf-conn.cases)
using correct conn unfolding binary-connectives-def apply auto
apply (cases c l rule: wf-conn.cases)
using correct conn unfolding binary-connectives-def by auto

```

lemma *conn-inj*:

```

fixes c ca :: 'v connective and l  $\psi$ s :: 'v propo list
assumes corr: wf-conn ca l
and corr': wf-conn c  $\psi$ s
and eq: conn ca l = conn c  $\psi$ s
shows ca = c  $\wedge$   $\psi$ s = l
using corr
proof (cases ca l rule: wf-conn.cases)
case (wf-conn-nullary v)
thus ca = c  $\wedge$   $\psi$ s = l using assms
by (metis conn.simps(1) conn.simps(2) conn.simps(3) wf-conn-list(1-3))
next
case (wf-conn-unary  $\psi'$ )
hence *: FNot  $\psi'$  = conn c  $\psi$ s using conn-inj-not eq assms by auto
hence c = ca by (metis conn-inj-not(1) corr' wf-conn-unary(2))
moreover have  $\psi$ s = l using * conn-inj-not(2) corr' wf-conn-unary(1) by force
ultimately show ca = c  $\wedge$   $\psi$ s = l by auto
next
case (wf-conn-binary  $\psi'$   $\psi''$ )
thus ca = c  $\wedge$   $\psi$ s = l
using eq corr' unfolding binary-connectives-def apply (case-tac ca, auto simp add: wf-conn-list)
using wf-conn-list(4-7) corr' by metis+
qed

```

4.3 Subformulas and properties

A characterization using sub-formulas is interesting for rewriting: we will define our relation on the sub-term level, and then lift the rewriting on the term-level. So the rewriting takes place on a subformula.

inductive *subformula* :: 'v propo \Rightarrow 'v propo \Rightarrow bool (infix \preceq 45) **for** φ **where**

subformula-refl[simp]: $\varphi \preceq \varphi$ |

subformula-into-subformula: $\psi \in \text{set } l \Rightarrow \text{wf-conn } c \ l \Rightarrow \varphi \preceq \psi \Rightarrow \varphi \preceq \text{conn } c \ l$

On the *subformula-into-subformula*, we can see why we use our *conn* representation: one case is enough to express the subformulas property instead of listing all the cases.

This is an example of a property related to subformulas.

lemma *subformula-in-subformula-not*:

shows b: FNot $\varphi \preceq \psi \Rightarrow \varphi \preceq \psi$

apply (induct rule: subformula.induct)

using subformula-into-subformula wf-conn-unary subformula-refl list.set-intros(1) subformula-refl

by (fastforce intro: subformula-into-subformula)+

lemma *subformula-in-binary-conn*:

assumes *conn*: $c \in \text{binary-connectives}$

shows $f \preceq \text{conn } c [f, g]$

and $g \preceq \text{conn } c [f, g]$

proof –

have a : $\text{wf-conn } c (f \# [g])$ **using** *conn wf-conn-binary binary-connectives-def* **by** *auto*

moreover **have** b : $f \preceq f$ **using** *subformula-refl* **by** *auto*

ultimately show $f \preceq \text{conn } c [f, g]$

by (*metis append-Nil in-set-conv-decomp subformula-into-subformula*)

next

have a : $\text{wf-conn } c ([f] @ [g])$ **using** *conn wf-conn-binary binary-connectives-def* **by** *auto*

moreover **have** b : $g \preceq g$ **using** *subformula-refl* **by** *auto*

ultimately show $g \preceq \text{conn } c [f, g]$ **using** *subformula-into-subformula* **by** *force*

qed

lemma *subformula-trans*:

$\psi \preceq \psi' \implies \varphi \preceq \psi \implies \varphi \preceq \psi'$

apply (*induct* ψ' *rule*: *subformula.inducts*)

by (*auto simp add*: *subformula-into-subformula*)

lemma *subformula-leaf*:

fixes $\varphi \psi :: 'v \text{ propo}$

assumes *incl*: $\varphi \preceq \psi$

and *simple*: $\psi = FT \vee \psi = FF \vee \psi = FVar x$

shows $\varphi = \psi$

using *incl simple*

by (*induct rule*: *subformula.induct*, *auto simp add*: *wf-conn-list*)

lemma *subformula-not-incl-eq*:

assumes $\varphi \preceq \text{conn } c l$

and *wf-conn* $c l$

and $\forall \psi. \psi \in \text{set } l \longrightarrow \neg \varphi \preceq \psi$

shows $\varphi = \text{conn } c l$

using *assms* **apply** (*induction* *conn* $c l$ *rule*: *subformula.induct*, *auto*)

using *conn-inj* **by** *blast*

lemma *wf-subformula-conn-cases*:

$\text{wf-conn } c l \implies \varphi \preceq \text{conn } c l \longleftrightarrow (\varphi = \text{conn } c l \vee (\exists \psi. \psi \in \text{set } l \wedge \varphi \preceq \psi))$

apply *standard*

using *subformula-not-incl-eq* **apply** *metis*

by (*auto simp add*: *subformula-into-subformula*)

lemma *subformula-decomp-explicit*[*simp*]:

$\varphi \preceq FAnd \psi \psi' \longleftrightarrow (\varphi = FAnd \psi \psi' \vee \varphi \preceq \psi \vee \varphi \preceq \psi')$ (**is** $?P FAnd$)

$\varphi \preceq FOr \psi \psi' \longleftrightarrow (\varphi = FOr \psi \psi' \vee \varphi \preceq \psi \vee \varphi \preceq \psi')$

$\varphi \preceq FEq \psi \psi' \longleftrightarrow (\varphi = FEq \psi \psi' \vee \varphi \preceq \psi \vee \varphi \preceq \psi')$

$\varphi \preceq FImp \psi \psi' \longleftrightarrow (\varphi = FImp \psi \psi' \vee \varphi \preceq \psi \vee \varphi \preceq \psi')$

proof –

have *wf-conn* $CAnd [\psi, \psi']$ **by** (*simp add*: *binary-connectives-def*)

hence $\varphi \preceq \text{conn } CAnd [\psi, \psi'] \longleftrightarrow (\varphi = \text{conn } CAnd [\psi, \psi'] \vee (\exists \psi''. \psi'' \in \text{set } [\psi, \psi'] \wedge \varphi \preceq \psi''))$

using *wf-subformula-conn-cases* **by** *metis*

thus $?P FAnd$ **by** *auto*

```

next
  have wf-conn COr [ $\psi$ ,  $\psi'$ ] by (simp add: binary-connectives-def)
  hence  $\varphi \preceq \text{conn } COr [\psi, \psi'] \longleftrightarrow (\varphi = \text{conn } COr [\psi, \psi'] \vee (\exists \psi''. \psi'' \in \text{set } [\psi, \psi'] \wedge \varphi \preceq \psi''))$ 
    using wf-subformula-conn-cases by metis
  thus ?P FOr by auto
next
  have wf-conn CEq [ $\psi$ ,  $\psi'$ ] by (simp add: binary-connectives-def)
  hence  $\varphi \preceq \text{conn } CEq [\psi, \psi'] \longleftrightarrow (\varphi = \text{conn } CEq [\psi, \psi'] \vee (\exists \psi''. \psi'' \in \text{set } [\psi, \psi'] \wedge \varphi \preceq \psi''))$ 
    using wf-subformula-conn-cases by metis
  thus ?P FEq by auto
next
  have wf-conn CImp [ $\psi$ ,  $\psi'$ ] by (simp add: binary-connectives-def)
  hence  $\varphi \preceq \text{conn } CImp [\psi, \psi'] \longleftrightarrow (\varphi = \text{conn } CImp [\psi, \psi'] \vee (\exists \psi''. \psi'' \in \text{set } [\psi, \psi'] \wedge \varphi \preceq \psi''))$ 
    using wf-subformula-conn-cases by metis
  thus ?P FImp by auto
qed

```

lemma wf-conn-helper-facts[iff]:

```

wf-conn CNot [ $\varphi$ ]
wf-conn CT []
wf-conn CF []
wf-conn (CVar  $x$ ) []
wf-conn CAnd [ $\varphi$ ,  $\psi$ ]
wf-conn COr [ $\varphi$ ,  $\psi$ ]
wf-conn CImp [ $\varphi$ ,  $\psi$ ]
wf-conn CEq [ $\varphi$ ,  $\psi$ ]
using wf-conn.intros unfolding binary-connectives-def by fastforce+

```

lemma exists-c-conn: $\exists c l. \varphi = \text{conn } c l \wedge \text{wf-conn } c l$
 by (cases φ) force+

lemma subformula-conn-decomp[simp]:

```

wf-conn  $c l \implies \varphi \preceq \text{conn } c l \longleftrightarrow (\varphi = \text{conn } c l \vee (\exists \psi \in \text{set } l. \varphi \preceq \psi))$ 
  apply auto

```

proof –

```

{
  fix  $\xi$ 
  have  $\varphi \preceq \xi \implies \xi = \text{conn } c l \implies \text{wf-conn } c l \implies \forall x::'a \text{ propo} \in \text{set } l. \neg \varphi \preceq x \implies \varphi = \text{conn } c l$ 
    apply (induct rule: subformula.induct)
    apply simp
    using conn-inj by blast
}
moreover assume wf-conn  $c l$  and  $\varphi \preceq \text{conn } c l$  and  $\forall x::'a \text{ propo} \in \text{set } l. \neg \varphi \preceq x$ 
ultimately show  $\varphi = \text{conn } c l$  by metis

```

next

```

fix  $\psi$ 
assume wf-conn  $c l$  and  $\psi \in \text{set } l$  and  $\varphi \preceq \psi$ 
thus  $\varphi \preceq \text{conn } c l$  using wf-subformula-conn-cases by blast
qed

```

lemma subformula-leaf-explicit[simp]:

```

 $\varphi \preceq FT \longleftrightarrow \varphi = FT$ 
 $\varphi \preceq FF \longleftrightarrow \varphi = FF$ 
 $\varphi \preceq FVar x \longleftrightarrow \varphi = FVar x$ 

```

apply *auto*
using *subformula-leaf* **by** *metis* +

The variables inside the formula gives precisely the variables that are needed for the formula.

primrec *vars-of-prop*:: '*v* *propo* \Rightarrow '*v* *set* **where**
vars-of-prop *FT* = {} |
vars-of-prop *FF* = {} |
vars-of-prop (*FVar* *x*) = {*x*} |
vars-of-prop (*FNot* φ) = *vars-of-prop* φ |
vars-of-prop (*FAnd* φ ψ) = *vars-of-prop* φ \cup *vars-of-prop* ψ |
vars-of-prop (*FOr* φ ψ) = *vars-of-prop* φ \cup *vars-of-prop* ψ |
vars-of-prop (*FImp* φ ψ) = *vars-of-prop* φ \cup *vars-of-prop* ψ |
vars-of-prop (*FEq* φ ψ) = *vars-of-prop* φ \cup *vars-of-prop* ψ

lemma *vars-of-prop-incl-conn*:

fixes $\xi \xi' :: 'v \text{ propo list}$ **and** $\psi :: 'v \text{ propo}$ **and** $c :: 'v \text{ connective}$
assumes *corr*: *wf-conn* *c* *l* **and** *incl*: $\psi \in \text{set } l$
shows *vars-of-prop* $\psi \subseteq \text{vars-of-prop } (\text{conn } c \text{ } l)$
proof (*cases c* *rule: connective-cases-arity-2*)
case *nullary*
hence *False* **using** *corr* *incl* **by** *auto*
thus *vars-of-prop* $\psi \subseteq \text{vars-of-prop } (\text{conn } c \text{ } l)$ **by** *blast*
next
case *binary* **note** *c* = *this*
then obtain *a* *b* **where** *ab*: *l* = [*a*, *b*]
using *wf-conn-bin-list-length* *list-length2-decomp* *corr* **by** *metis*
hence $\psi = a \vee \psi = b$ **using** *incl* **by** *auto*
thus *vars-of-prop* $\psi \subseteq \text{vars-of-prop } (\text{conn } c \text{ } l)$
using *ab* *c* **unfolding** *binary-connectives-def* **by** *auto*
next
case *unary* **note** *c* = *this*
fix $\varphi :: 'v \text{ propo}$
have *l* = [ψ] **using** *corr* *c* *incl* *split-list* **by** *force*
thus *vars-of-prop* $\psi \subseteq \text{vars-of-prop } (\text{conn } c \text{ } l)$ **using** *c* **by** *auto*
qed

The set of variables is compatible with the subformula order.

lemma *subformula-vars-of-prop*:

$\varphi \preceq \psi \implies \text{vars-of-prop } \varphi \subseteq \text{vars-of-prop } \psi$
apply (*induct* *rule: subformula.induct*)
apply *simp*
using *vars-of-prop-incl-conn* **by** *blast*

4.4 Positions

Instead of 1 or 2 we use *L* or *R*

datatype *sign* = *L* | *R*

We use *nil* instead of ε .

fun *pos* :: '*v* *propo* \Rightarrow *sign* *list* *set* **where**
pos *FF* = {} |
pos *FT* = {} |
pos (*FVar* *x*) = { $\{\}$ } |

$\text{pos } (F\text{And } \varphi \ \psi) = \{\square\} \cup \{L \# p \mid p. p \in \text{pos } \varphi\} \cup \{R \# p \mid p. p \in \text{pos } \psi\} \mid$
 $\text{pos } (F\text{Or } \varphi \ \psi) = \{\square\} \cup \{L \# p \mid p. p \in \text{pos } \varphi\} \cup \{R \# p \mid p. p \in \text{pos } \psi\} \mid$
 $\text{pos } (F\text{Eq } \varphi \ \psi) = \{\square\} \cup \{L \# p \mid p. p \in \text{pos } \varphi\} \cup \{R \# p \mid p. p \in \text{pos } \psi\} \mid$
 $\text{pos } (F\text{Imp } \varphi \ \psi) = \{\square\} \cup \{L \# p \mid p. p \in \text{pos } \varphi\} \cup \{R \# p \mid p. p \in \text{pos } \psi\} \mid$
 $\text{pos } (F\text{Not } \varphi) = \{\square\} \cup \{L \# p \mid p. p \in \text{pos } \varphi\}$

lemma *finite-pos*: *finite* (*pos* φ)
by (*induct* φ , *auto*)

lemma *finite-inj-comp-set*:

fixes $s :: 'v \text{ set}$
assumes *finite*: *finite* s
and *inj*: *inj* f
shows $\text{card } (\{f \ p \mid p. p \in s\}) = \text{card } s$
using *finite*

proof (*induct* s *rule*: *finite-induct*)

show $\text{card } \{f \ p \mid p. p \in \{\}\} = \text{card } \{\}$ **by** *auto*

next

fix $x :: 'v$ **and** $s :: 'v \text{ set}$
assume f : *finite* s **and** *notin*: $x \notin s$
and *IH*: $\text{card } \{f \ p \mid p. p \in s\} = \text{card } s$
have f' : *finite* $\{f \ p \mid p. p \in \text{insert } x \ s\}$ **using** f **by** *auto*
have *notin'*: $f \ x \notin \{f \ p \mid p. p \in s\}$ **using** *notin* *inj* *injD* **by** *fastforce*
have $\{f \ p \mid p. p \in \text{insert } x \ s\} = \text{insert } (f \ x) \ \{f \ p \mid p. p \in s\}$ **by** *auto*
hence $\text{card } \{f \ p \mid p. p \in \text{insert } x \ s\} = 1 + \text{card } \{f \ p \mid p. p \in s\}$
using *finite* *card-insert-disjoint* f' *notin'* **by** *auto*
moreover **have** $\dots = \text{card } (\text{insert } x \ s)$ **using** *notin* f *IH* **by** *auto*
finally **show** $\text{card } \{f \ p \mid p. p \in \text{insert } x \ s\} = \text{card } (\text{insert } x \ s)$.

qed

lemma *cons-inject*:

inj (*op* $\#$ s)
by (*meson* *injI* *list.inject*)

lemma *finite-insert-nil-cons*:

finite $s \implies \text{card } (\text{insert } \square \ \{L \# p \mid p. p \in s\}) = 1 + \text{card } \{L \# p \mid p. p \in s\}$
using *card-insert-disjoint* **by** *auto*

lemma *card-not[simp]*:

$\text{card } (\text{pos } (F\text{Not } \varphi)) = 1 + \text{card } (\text{pos } \varphi)$

by (*simp* *add*: *cons-inject* *finite-inj-comp-set* *finite-pos*)

lemma *card-seperate*:

assumes *finite* $s1$ **and** *finite* $s2$
shows $\text{card } (\{L \# p \mid p. p \in s1\} \cup \{R \# p \mid p. p \in s2\}) = \text{card } (\{L \# p \mid p. p \in s1\})$
 $+ \text{card } (\{R \# p \mid p. p \in s2\})$ (**is** $\text{card } (?L \cup ?R) = \text{card } ?L + \text{card } ?R$)

proof –

have *finite* $?L$ **using** *assms* **by** *auto*
moreover **have** *finite* $?R$ **using** *assms* **by** *auto*
moreover **have** $?L \cap ?R = \{\}$ **by** *blast*
ultimately **show** *thesis* **using** *assms* *card-Un-disjoint* **by** *blast*

qed

definition *prop-size* **where** *prop-size* $\varphi = \text{card } (\text{pos } \varphi)$

lemma *prop-size-vars-of-prop*:

fixes $\varphi :: 'v \text{ propo}$

shows $\text{card } (\text{vars-of-prop } \varphi) \leq \text{prop-size } \varphi$

unfolding *prop-size-def* **apply** (*induct* φ , *auto simp add: cons-inject finite-inj-comp-set finite-pos*)

proof –

fix $\varphi 1 \ \varphi 2 :: 'v \text{ propo}$

assume *IH1*: $\text{card } (\text{vars-of-prop } \varphi 1) \leq \text{card } (\text{pos } \varphi 1)$

and *IH2*: $\text{card } (\text{vars-of-prop } \varphi 2) \leq \text{card } (\text{pos } \varphi 2)$

let $?L = \{L \# p \mid p. p \in \text{pos } \varphi 1\}$

let $?R = \{R \# p \mid p. p \in \text{pos } \varphi 2\}$

have $\text{card } (?L \cup ?R) = \text{card } ?L + \text{card } ?R$

using *card-seperate finite-pos* **by** *blast*

moreover **have** $\dots = \text{card } (\text{pos } \varphi 1) + \text{card } (\text{pos } \varphi 2)$

by (*simp add: cons-inject finite-inj-comp-set finite-pos*)

moreover **have** $\dots \geq \text{card } (\text{vars-of-prop } \varphi 1) + \text{card } (\text{vars-of-prop } \varphi 2)$ **using** *IH1 IH2* **by** *arith*

hence $\dots \geq \text{card } (\text{vars-of-prop } \varphi 1 \cup \text{vars-of-prop } \varphi 2)$ **using** *card-Un-le le-trans* **by** *blast*

ultimately

show $\text{card } (\text{vars-of-prop } \varphi 1 \cup \text{vars-of-prop } \varphi 2) \leq \text{Suc } (\text{card } (?L \cup ?R))$

$\text{card } (\text{vars-of-prop } \varphi 1 \cup \text{vars-of-prop } \varphi 2) \leq \text{Suc } (\text{card } (?L \cup ?R))$

$\text{card } (\text{vars-of-prop } \varphi 1 \cup \text{vars-of-prop } \varphi 2) \leq \text{Suc } (\text{card } (?L \cup ?R))$

$\text{card } (\text{vars-of-prop } \varphi 1 \cup \text{vars-of-prop } \varphi 2) \leq \text{Suc } (\text{card } (?L \cup ?R))$

by *auto*

qed

value *pos* (*FImp* (*FAnd* (*FVar* *P*) (*FVar* *Q*)) (*FOr* (*FVar* *P*) (*FVar* *Q*)))

inductive *path-to* :: *sign list* $\Rightarrow 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **where**

path-to-refl[*intro*]: *path-to* $[] \ \varphi \ \varphi \mid$

path-to-l: $c \in \text{binary-connectives} \vee c = \text{CNot} \Longrightarrow \text{wf-conn } c \ (\varphi \# l) \Longrightarrow \text{path-to } p \ \varphi \ \varphi'$

$\Longrightarrow \text{path-to } (L \# p) \ (\text{conn } c \ (\varphi \# l)) \ \varphi' \mid$

path-to-r: $c \in \text{binary-connectives} \Longrightarrow \text{wf-conn } c \ (\psi \# \varphi \# []) \Longrightarrow \text{path-to } p \ \varphi \ \varphi'$

$\Longrightarrow \text{path-to } (R \# p) \ (\text{conn } c \ (\psi \# \varphi \# [])) \ \varphi'$

There is a deep link between subformulas and pathes: a (correct) path leads to a subformula and a subformula is associated to a given path.

lemma *path-to-subformula*:

path-to $p \ \varphi \ \varphi' \Longrightarrow \varphi' \preceq \varphi$

apply (*induct rule: path-to.induct*)

apply *simp*

apply (*metis list.set-intros*(1) *subformula-into-subformula*)

using *subformula-trans subformula-in-binary-conn*(2) **by** *metis*

lemma *subformula-path-exists*:

fixes $\varphi \ \varphi' :: 'v \text{ propo}$

shows $\varphi' \preceq \varphi \Longrightarrow \exists p. \text{path-to } p \ \varphi \ \varphi'$

proof (*induct rule: subformula.induct*)

case *subformula-refl*

have *path-to* $[] \ \varphi' \ \varphi'$ **by** *auto*

```

thus  $\exists p. \text{path-to } p \ \varphi' \ \varphi'$  by metis
next
case (subformula-into-subformula  $\psi \ l \ c$ )
note  $wf = \text{this}(2)$  and  $IH = \text{this}(4)$  and  $\psi = \text{this}(1)$ 
then obtain  $p$  where  $p: \text{path-to } p \ \psi \ \varphi'$  by metis
{
  fix  $x :: 'v$ 
  assume  $c = CT \vee c = CF \vee c = CVar \ x$ 
  hence False using subformula-into-subformula by auto
  hence  $\exists p. \text{path-to } p \ (\text{conn } c \ l) \ \varphi'$  by blast
}
moreover {
  assume  $c: c = CNot$ 
  hence  $l = [\psi]$  using  $wf \ \psi \ \text{wf-conn-Not-decomp}$  by fastforce
  hence  $\text{path-to } (L \ \# \ p) \ (\text{conn } c \ l) \ \varphi'$  by (metis  $c \ \text{wf-conn-unary } p \ \text{path-to-l}$ )
  hence  $\exists p. \text{path-to } p \ (\text{conn } c \ l) \ \varphi'$  by blast
}
moreover {
  assume  $c: c \in \text{binary-connectives}$ 
  obtain  $a \ b$  where  $ab: [a, b] = l$  using subformula-into-subformula  $c \ \text{wf-conn-bin-list-length}$ 
  list-length2-decomp by metis
  hence  $a = \psi \vee b = \psi$  using  $\psi$  by auto
  hence  $\text{path-to } (L \ \# \ p) \ (\text{conn } c \ l) \ \varphi' \vee \text{path-to } (R \ \# \ p) \ (\text{conn } c \ l) \ \varphi'$  using  $c \ \text{path-to-l}$ 
  path-to-r  $p \ ab$  by (metis wf-conn-binary)
  hence  $\exists p. \text{path-to } p \ (\text{conn } c \ l) \ \varphi'$  by blast
}
ultimately show  $\exists p. \text{path-to } p \ (\text{conn } c \ l) \ \varphi'$  using connective-cases-arity by metis
qed

```

```

fun replace-at ::  $\text{sign list} \Rightarrow 'v \ \text{propo} \Rightarrow 'v \ \text{propo} \Rightarrow 'v \ \text{propo}$  where
replace-at [] -  $\psi = \psi$  |
replace-at ( $L \ \# \ l$ ) (FAnd  $\varphi \ \varphi'$ )  $\psi = \text{FAnd } (\text{replace-at } l \ \varphi \ \psi) \ \varphi'$  |
replace-at ( $R \ \# \ l$ ) (FAnd  $\varphi \ \varphi'$ )  $\psi = \text{FAnd } \varphi \ (\text{replace-at } l \ \varphi' \ \psi)$  |
replace-at ( $L \ \# \ l$ ) (FOr  $\varphi \ \varphi'$ )  $\psi = \text{FOr } (\text{replace-at } l \ \varphi \ \psi) \ \varphi'$  |
replace-at ( $R \ \# \ l$ ) (FOr  $\varphi \ \varphi'$ )  $\psi = \text{FOr } \varphi \ (\text{replace-at } l \ \varphi' \ \psi)$  |
replace-at ( $L \ \# \ l$ ) (FEq  $\varphi \ \varphi'$ )  $\psi = \text{FEq } (\text{replace-at } l \ \varphi \ \psi) \ \varphi'$  |
replace-at ( $R \ \# \ l$ ) (FEq  $\varphi \ \varphi'$ )  $\psi = \text{FEq } \varphi \ (\text{replace-at } l \ \varphi' \ \psi)$  |
replace-at ( $L \ \# \ l$ ) (FImp  $\varphi \ \varphi'$ )  $\psi = \text{FImp } (\text{replace-at } l \ \varphi \ \psi) \ \varphi'$  |
replace-at ( $R \ \# \ l$ ) (FImp  $\varphi \ \varphi'$ )  $\psi = \text{FImp } \varphi \ (\text{replace-at } l \ \varphi' \ \psi)$  |
replace-at ( $L \ \# \ l$ ) (FNot  $\varphi$ )  $\psi = \text{FNot } (\text{replace-at } l \ \varphi \ \psi)$ 

```

5 Semantics over the syntax

Given the syntax defined above, we define a semantics, by defining an evaluation function *eval*. This function is the bridge between the logic as we define it here and the built-in logic of Isabelle.

```

fun eval ::  $('v \Rightarrow \text{bool}) \Rightarrow 'v \ \text{propo} \Rightarrow \text{bool}$  (infix  $\models$  50) where
 $\mathcal{A} \models FT = \text{True}$  |
 $\mathcal{A} \models FF = \text{False}$  |
 $\mathcal{A} \models \text{FVar } v = (\mathcal{A} \ v)$  |
 $\mathcal{A} \models \text{FNot } \varphi = (\neg(\mathcal{A} \models \varphi))$  |
 $\mathcal{A} \models \text{FAnd } \varphi_1 \ \varphi_2 = (\mathcal{A} \models \varphi_1 \wedge \mathcal{A} \models \varphi_2)$  |
 $\mathcal{A} \models \text{FOr } \varphi_1 \ \varphi_2 = (\mathcal{A} \models \varphi_1 \vee \mathcal{A} \models \varphi_2)$  |
 $\mathcal{A} \models \text{FImp } \varphi_1 \ \varphi_2 = (\mathcal{A} \models \varphi_1 \longrightarrow \mathcal{A} \models \varphi_2)$  |
 $\mathcal{A} \models \text{FEq } \varphi_1 \ \varphi_2 = (\mathcal{A} \models \varphi_1 \longleftrightarrow \mathcal{A} \models \varphi_2)$ 

```


definition *evalf* (**infix** \models_f 50) **where**
evalf $\varphi \psi = (\forall A. A \models \varphi \longrightarrow A \models \psi)$

The deduction rule is in the book. And the proof looks like to the one of the book.

lemma *deduction-rule*:

$(\varphi \models_f \psi) \longleftrightarrow (\forall A. (A \models FImp \varphi \psi))$

proof

assume $H: \varphi \models_f \psi$

{
fix A

“Suppose that φ entails ψ (assumption $\varphi \models_f \psi$) and let A be an arbitrary $'v$ -valuation. We need to show $A \models FImp \varphi \psi$. ”

{

If $A \varphi = (1::'b)$, then $A \varphi = (1::'b)$, because φ entails ψ , and therefore $A \models FImp \varphi \psi$.

assume $A \models \varphi$
hence $A \models \psi$ **using** H **unfolding** *evalf-def* **by** *metis*
hence $A \models FImp \varphi \psi$ **by** *auto*

}

moreover {

For otherwise, if $A \varphi = (0::'b)$, then $A \models FImp \varphi \psi$ holds by definition, independently of the value of $A \models \psi$.

assume $\neg A \models \varphi$
hence $A \models FImp \varphi \psi$ **by** *auto*

}

In both cases $A \models FImp \varphi \psi$.

ultimately have $A \models FImp \varphi \psi$ **by** *blast*

}

thus $\forall A. A \models FImp \varphi \psi$ **by** *blast*

next

show $\forall A. A \models FImp \varphi \psi \implies \varphi \models_f \psi$

proof (*rule ccontr*)

assume $\neg \varphi \models_f \psi$

then obtain A **where** $A \models \varphi \wedge \neg A \models \psi$ **using** *evalf-def* **by** *metis*

hence $\neg A \models FImp \varphi \psi$ **by** *auto*

moreover assume $\forall A. A \models FImp \varphi \psi$

ultimately show *False* **by** *blast*

qed

qed

A shorter proof:

lemma $\varphi \models_f \psi \longleftrightarrow (\forall A. A \models FImp \varphi \psi)$

by (*simp add: evalf-def*)

definition *same-over-set::* $('v \Rightarrow bool) \Rightarrow ('v \Rightarrow bool) \Rightarrow 'v \text{ set} \Rightarrow bool$ **where**

same-over-set $A B S = (\forall c \in S. A c = B c)$

If two mapping A and B have the same value over the variables, then the same formula are satisfiable.

lemma *same-over-set-eval*:

```

assumes same-over-set  $A\ B$  (vars-of-prop  $\varphi$ )
shows  $A \models \varphi \longleftrightarrow B \models \varphi$ 
using assms unfolding same-over-set-def by (induct  $\varphi$ , auto)

```

```

end
theory Prop-Abstract-Transformation
imports Main Prop-Logic Wellfounded-More

```

```

begin

```

This file is devoted to abstract properties of the transformations, like consistency preservation and lifting from terms to proposition.

6 Rewrite systems and properties

6.1 Lifting of rewrite rules

We can lift a rewrite relation r over a full formula: the relation r works on terms, while *propo-rew-step* works on formulas.

```

inductive propo-rew-step :: ('v propo  $\Rightarrow$  'v propo  $\Rightarrow$  bool)  $\Rightarrow$  'v propo  $\Rightarrow$  'v propo  $\Rightarrow$  bool
  for  $r :: 'v propo \Rightarrow 'v propo \Rightarrow$  bool where
    global-rel:  $r\ \varphi\ \psi \Longrightarrow$  propo-rew-step  $r\ \varphi\ \psi$  |
    propo-rew-one-step-lift: propo-rew-step  $r\ \varphi\ \varphi' \Longrightarrow$  wf-conn  $c\ (\psi s\ @\ \varphi\ \# \psi s')$ 
       $\Longrightarrow$  propo-rew-step  $r\ (\text{conn } c\ (\psi s\ @\ \varphi\ \# \psi s'))\ (\text{conn } c\ (\psi s\ @\ \varphi' \# \psi s'))$ 

```

Here is a more precise link between the lifting and the subformulas: if a rewriting takes place between φ and φ' , then there are two subformulas ψ in φ and ψ' in φ' , ψ' is the result of the rewriting of r on ψ .

This lemma is only a health condition:

```

lemma propo-rew-step-subformula-imp:
shows propo-rew-step  $r\ \varphi\ \varphi' \Longrightarrow \exists\ \psi\ \psi'.\ \psi \preceq \varphi \wedge \psi' \preceq \varphi' \wedge r\ \psi\ \psi'$ 
  apply (induct rule: propo-rew-step.induct)
  using subformula.simps subformula-into-subformula apply blast
  using wf-conn-no-arity-change subformula-into-subformula wf-conn-no-arity-change-helper
  in-set-conv-decomp by metis

```

The converse is moreover true: if there is a ψ and ψ' , then every formula φ containing ψ , can be rewritten into a formula φ' , such that it contains φ' .

```

lemma propo-rew-step-subformula-rec:
  fixes  $\psi\ \psi'\ \varphi :: 'v propo$ 
  shows  $\psi \preceq \varphi \Longrightarrow r\ \psi\ \psi' \Longrightarrow (\exists\ \varphi'.\ \psi' \preceq \varphi' \wedge \text{propo-rew-step } r\ \varphi\ \varphi')$ 
proof (induct  $\varphi$  rule: subformula.induct)
  case subformula-refl
  hence propo-rew-step  $r\ \psi\ \psi'$  using propo-rew-step.intros by auto
  moreover have  $\psi' \preceq \psi'$  using Prop-Logic.subformula-refl by auto
  ultimately show  $\exists\ \varphi'.\ \psi' \preceq \varphi' \wedge \text{propo-rew-step } r\ \psi\ \varphi'$  by fastforce
next
  case (subformula-into-subformula  $\psi''\ l\ c$ )
  note  $IH = \text{this}(4)$  and  $r = \text{this}(5)$  and  $\psi'' = \text{this}(1)$  and  $wf = \text{this}(2)$  and  $incl = \text{this}(3)$ 
  then obtain  $\varphi'$  where  $*: \psi' \preceq \varphi' \wedge \text{propo-rew-step } r\ \psi''\ \varphi'$  by metis
  moreover obtain  $\xi\ \xi' :: 'v propo\ \text{list}$  where
     $l: l = \xi\ @\ \psi''\ \# \xi'$  using List.split-list  $\psi''$  by metis

```

ultimately have *propo-rew-step* r (*conn* c l) (*conn* c ($\xi @ \varphi' \# \xi'$))
 using *propo-rew-step.intros*(2) *wf* **by** *metis*
 moreover have $\psi' \preceq \text{conn } c (\xi @ \varphi' \# \xi')$
 using *wf * wf-conn-no-arity-change Prop-Logic.subformula-into-subformula*
by (*metis (no-types) in-set-conv-decomp l wf-conn-no-arity-change-helper*)
 ultimately show $\exists \varphi'. \psi' \preceq \varphi' \wedge \text{propo-rew-step } r (\text{conn } c l) \varphi'$ **by** *metis*
qed

lemma *propo-rew-step-subformula*:
 $(\exists \psi \psi'. \psi \preceq \varphi \wedge r \psi \psi') \longleftrightarrow (\exists \varphi'. \text{propo-rew-step } r \varphi \varphi')$
 using *propo-rew-step-subformula-imp propo-rew-step-subformula-rec* **by** *metis*+

lemma *consistency-decompose-into-list*:
 assumes *wf*: *wf-conn* c l **and** *wf'*: *wf-conn* c l'
 and *same*: $\forall n. (A \models l ! n \longleftrightarrow (A \models l' ! n))$
 shows $(A \models \text{conn } c l) = (A \models \text{conn } c l')$
proof (*cases c rule: connective-cases-arity-2*)
 case *nullary*
 thus $(A \models \text{conn } c l) \longleftrightarrow (A \models \text{conn } c l')$ **using** *wf wf'* **by** *auto*
next
 case *unary note* $c = \text{this}$
 then obtain a where $l: l = [a]$ **using** *wf-conn-Not-decomp wf* **by** *metis*
 obtain a' where $l': l' = [a']$ **using** *wf-conn-Not-decomp wf' c* **by** *metis*
 have $A \models a \longleftrightarrow A \models a'$ **using** $l l'$ **by** (*metis nth-Cons-0 same*)
 thus $A \models \text{conn } c l \longleftrightarrow A \models \text{conn } c l'$ **using** $l l' c$ **by** *auto*
next
 case *binary note* $c = \text{this}$
 then obtain $a b$ where $l: l = [a, b]$
using *wf-conn-bin-list-length list-length2-decomp wf* **by** *metis*
 obtain $a' b'$ where $l': l' = [a', b']$
using *wf-conn-bin-list-length list-length2-decomp wf' c* **by** *metis*

 have $p: A \models a \longleftrightarrow A \models a' \wedge A \models b \longleftrightarrow A \models b'$
using $l l'$ **same** **by** (*metis diff-Suc-1 nth-Cons' nat.distinct(2)*)
 show $A \models \text{conn } c l \longleftrightarrow A \models \text{conn } c l'$
using *wf c p unfolding binary-connectives-def l l'* **by** *auto*
qed

Relation between *propo-rew-step* and the rewriting we have seen before: *propo-rew-step* $r \varphi \varphi'$ means that we rewrite ψ inside φ (ie at a path p) into ψ' .

lemma *propo-rew-step-rewrite*:
 fixes $\varphi \varphi' :: 'v \text{ propo}$ **and** $r :: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$
 assumes *propo-rew-step* $r \varphi \varphi'$
 shows $\exists \psi \psi' p. r \psi \psi' \wedge \text{path-to } p \varphi \psi \wedge \text{replace-at } p \varphi \psi' = \varphi'$
using *assms*
proof (*induct rule: propo-rew-step.induct*)
 case (*global-rel* $\varphi \psi$)
 moreover have *path-to* $\square \varphi \varphi$ **by** *auto*
 moreover have *replace-at* $\square \varphi \psi = \psi$ **by** *auto*
 ultimately show *?case* **by** *metis*
next
 case (*propo-rew-one-step-lift* $\varphi \varphi' c \xi \xi'$) **note** *rel = this(1)* **and** *IH0 = this(2)* **and** *corr = this(3)*
 obtain $\psi \psi' p$ where *IH*: $r \psi \psi' \wedge \text{path-to } p \varphi \psi \wedge \text{replace-at } p \varphi \psi' = \varphi'$ **using** *IH0* **by** *metis*

 {

```

fix x :: 'v
assume c = CT ∨ c = CF ∨ c = CVar x
hence False using corr by auto
hence ∃ψ ψ' p. r ψ ψ' ∧ path-to p (conn c (ξ@ (φ # ξ'))) ψ
      ∧ replace-at p (conn c (ξ@ (φ # ξ'))) ψ' = conn c (ξ@ (φ' # ξ'))
  by fast
}
moreover {
  assume c: c = CNot
  hence empty: ξ = [] ξ' = [] using corr by auto
  have path-to (L#p) (conn c (ξ@ (φ # ξ'))) ψ
    using c empty IH wf-conn-unary path-to-l by fastforce
  moreover have replace-at (L#p) (conn c (ξ@ (φ # ξ'))) ψ' = conn c (ξ@ (φ' # ξ'))
    using c empty IH by auto
  ultimately have ∃ψ ψ' p. r ψ ψ' ∧ path-to p (conn c (ξ@ (φ # ξ'))) ψ
    ∧ replace-at p (conn c (ξ@ (φ # ξ'))) ψ' = conn c (ξ@ (φ' # ξ'))
  using IH by metis
}
moreover {
  assume c: c ∈ binary-connectives
  have length (ξ@ φ # ξ') = 2 using wf-conn-bin-list-length corr c by metis
  hence length ξ + length ξ' = 1 by auto
  hence ld: (length ξ = 1 ∧ length ξ' = 0) ∨ (length ξ = 0 ∧ length ξ' = 1) by arith
  obtain a b where ab: (ξ = [] ∧ ξ' = [b]) ∨ (ξ = [a] ∧ ξ' = [])
    using ld by (case-tac ξ, case-tac ξ', auto)
  {
    assume φ: ξ = [] ∧ ξ' = [b]
    have path-to (L#p) (conn c (ξ@ (φ # ξ'))) ψ
      using φ c IH ab corr by (simp add: path-to-l)
    moreover have replace-at (L#p) (conn c (ξ@ (φ # ξ'))) ψ' = conn c (ξ@ (φ' # ξ'))
      using c IH ab φ unfolding binary-connectives-def by auto
    ultimately have ∃ψ ψ' p. r ψ ψ' ∧ path-to p (conn c (ξ@ (φ # ξ'))) ψ
      ∧ replace-at p (conn c (ξ@ (φ # ξ'))) ψ' = conn c (ξ@ (φ' # ξ'))
      using IH by metis
  }
  moreover {
    assume φ: ξ = [a] ξ' = []
    hence path-to (R#p) (conn c (ξ@ (φ # ξ'))) ψ
      using c IH corr path-to-r corr φ by (simp add: path-to-r)
    moreover have replace-at (R#p) (conn c (ξ@ (φ # ξ'))) ψ' = conn c (ξ@ (φ' # ξ'))
      using c IH ab φ unfolding binary-connectives-def by auto
    ultimately have ?case using IH by metis
  }
  ultimately have ?case using ab by blast
}
ultimately show ?case using connective-cases-arity by blast
qed

```

6.2 Consistency preservation

We define *preserves-un-sat*: it means that a relation preserves consistency.

definition *preserves-un-sat* **where**

preserves-un-sat $r \longleftrightarrow (\forall \varphi \psi. r \varphi \psi \longrightarrow (\forall A. A \models \varphi \longleftrightarrow A \models \psi))$

lemma *propo-rew-step-preservers-val-explicit*:

propo-rew-step $r \varphi \psi \implies \text{preserves-un-sat } r \implies \text{propo-rew-step } r \varphi \psi \implies (\forall A. A \models \varphi \longleftrightarrow A \models \psi)$

unfolding *preserves-un-sat-def*

proof (*induction rule: propo-rew-step.induct*)

case *global-rel*

thus *?case* **by** *simp*

next

case (*propo-rew-one-step-lift* $\varphi \varphi' c \xi \xi'$) **note** $\text{rel} = \text{this}(1)$ **and** $\text{wf} = \text{this}(2)$

and $\text{IH} = \text{this}(3)[\text{OF } \text{this}(4) \text{ this}(1)]$ **and** $\text{consistent} = \text{this}(4)$

{

fix A

from IH **have** $\forall n. (A \models (\xi @ \varphi \# \xi') ! n) = (A \models (\xi @ \varphi' \# \xi') ! n)$

by (*metis* (*mono-tags*, *hide-lams*) *list-update-length* *nth-Cons-0* *nth-append-length-plus* *nth-list-update-neq*)

hence $(A \models \text{conn } c (\xi @ \varphi \# \xi')) = (A \models \text{conn } c (\xi @ \varphi' \# \xi'))$

by (*meson* *consistency-decompose-into-list* *wf* *wf-conn-no-arity-change-helper* *wf-conn-no-arity-change*)

}

thus $\forall A. A \models \text{conn } c (\xi @ \varphi \# \xi') \longleftrightarrow A \models \text{conn } c (\xi @ \varphi' \# \xi')$ **by** *auto*

qed

lemma *propo-rew-step-preservers-val'*:

assumes *preserves-un-sat* r

shows *preserves-un-sat* (*propo-rew-step* r)

using *assms* **by** (*simp* *add: preserves-un-sat-def propo-rew-step-preservers-val-explicit*)

lemma *preserves-un-sat-OO[intro]*:

preserves-un-sat $f \implies \text{preserves-un-sat } g \implies \text{preserves-un-sat } (f \text{ OO } g)$

unfolding *preserves-un-sat-def* **by** *auto*

lemma *star-consistency-preservation-explicit*:

assumes (*propo-rew-step* r)^{**} $\varphi \psi$ **and** *preserves-un-sat* r

shows $\forall A. A \models \varphi \longleftrightarrow A \models \psi$

using *assms* **by** (*induct rule: rtranclp-induct*)

(*auto* *simp* *add: propo-rew-step-preservers-val-explicit*)

lemma *star-consistency-preservation*:

preserves-un-sat $r \implies \text{preserves-un-sat } (\text{propo-rew-step } r)^{**}$

by (*simp* *add: star-consistency-preservation-explicit preserves-un-sat-def*)

6.3 Full Lifting

In the previous a relation was lifted to a formula, now we define the relation such it is applied as long as possible. The definition is thus simply: it can be derived and nothing more can be derived.

lemma *full-ropo-rew-step-preservers-val[simp]*:

preserves-un-sat $r \implies \text{preserves-un-sat } (\text{full } (\text{propo-rew-step } r))$

by (*metis* *full-def* *preserves-un-sat-def* *star-consistency-preservation*)

lemma *full-propo-rew-step-subformula*:

full (*propo-rew-step* r) $\varphi' \varphi \implies \neg(\exists \psi \psi'. \psi \preceq \varphi \wedge r \psi \psi')$

unfolding *full-def* **using** *propo-rew-step-subformula-rec* **by** *metis*

7 Transformation testing

7.1 Definition and first properties

To prove correctness of our transformation, we create a *all-subformula-st* predicate. It tests recursively all subformulas. At each step, the actual formula is tested. The aim of this *test-symb* function is to test locally some properties of the formulas (i.e. at the level of the connective or at first level). This allows a clause description between the rewrite relation and the *test-symb*

definition *all-subformula-st* :: ('a propo \Rightarrow bool) \Rightarrow 'a propo \Rightarrow bool **where**
all-subformula-st test-symb $\varphi \equiv \forall \psi. \psi \preceq \varphi \longrightarrow \text{test-symb } \psi$

lemma *test-symb-imp-all-subformula-st[simp]*:
test-symb FT \Longrightarrow *all-subformula-st test-symb FT*
test-symb FF \Longrightarrow *all-subformula-st test-symb FF*
test-symb (FVar x) \Longrightarrow *all-subformula-st test-symb (FVar x)*
unfolding *all-subformula-st-def* **using** *subformula-leaf* **by** *metis+*

lemma *all-subformula-st-test-symb-true-phi*:
all-subformula-st test-symb $\varphi \Longrightarrow \text{test-symb } \varphi$
unfolding *all-subformula-st-def* **by** *auto*

lemma *all-subformula-st-decomp-imp*:
wf-conn c l \Longrightarrow (*test-symb (conn c l)* \wedge ($\forall \varphi \in \text{set } l. \text{all-subformula-st test-symb } \varphi$))
 \Longrightarrow *all-subformula-st test-symb (conn c l)*
unfolding *all-subformula-st-def* **by** *auto*

To ease the finding of proofs, we give some explicit theorem about the decomposition.

lemma *all-subformula-st-decomp-rec*:
all-subformula-st test-symb (conn c l) \Longrightarrow *wf-conn c l*
 \Longrightarrow (*test-symb (conn c l)* \wedge ($\forall \varphi \in \text{set } l. \text{all-subformula-st test-symb } \varphi$))
unfolding *all-subformula-st-def* **by** *auto*

lemma *all-subformula-st-decomp*:
fixes *c* :: 'v connective **and** *l* :: 'v propo list
assumes *wf-conn c l*
shows *all-subformula-st test-symb (conn c l)*
 \longleftrightarrow (*test-symb (conn c l)* \wedge ($\forall \varphi \in \text{set } l. \text{all-subformula-st test-symb } \varphi$))
using *assms all-subformula-st-decomp-rec all-subformula-st-decomp-imp* **by** *metis*

lemma *helper-fact*: *c* \in *binary-connectives* \longleftrightarrow (*c* = *COr* \vee *c* = *CAnd* \vee *c* = *CEq* \vee *c* = *CImp*)
unfolding *binary-connectives-def* **by** *auto*

lemma *all-subformula-st-decomp-explicit[simp]*:
fixes $\varphi \psi$:: 'v propo
shows *all-subformula-st test-symb (FAnd $\varphi \psi$)*
 \longleftrightarrow (*test-symb (FAnd $\varphi \psi$)* \wedge *all-subformula-st test-symb* φ \wedge *all-subformula-st test-symb* ψ)
and *all-subformula-st test-symb (FOr $\varphi \psi$)*
 \longleftrightarrow (*test-symb (FOr $\varphi \psi$)* \wedge *all-subformula-st test-symb* φ \wedge *all-subformula-st test-symb* ψ)
and *all-subformula-st test-symb (FNot φ)*
 \longleftrightarrow (*test-symb (FNot φ)* \wedge *all-subformula-st test-symb* φ)
and *all-subformula-st test-symb (FEq $\varphi \psi$)*
 \longleftrightarrow (*test-symb (FEq $\varphi \psi$)* \wedge *all-subformula-st test-symb* φ \wedge *all-subformula-st test-symb* ψ)
and *all-subformula-st test-symb (FImp $\varphi \psi$)*
 \longleftrightarrow (*test-symb (FImp $\varphi \psi$)* \wedge *all-subformula-st test-symb* φ \wedge *all-subformula-st test-symb* ψ)

proof –

have $\text{all-subformula-st test-symb } (F\text{And } \varphi \psi) \longleftrightarrow \text{all-subformula-st test-symb } (\text{conn } C\text{And } [\varphi, \psi])$
by *auto*
moreover have $\dots \longleftrightarrow \text{test-symb } (\text{conn } C\text{And } [\varphi, \psi]) \wedge (\forall \xi \in \text{set } [\varphi, \psi]. \text{all-subformula-st test-symb } \xi)$
using *all-subformula-st-decomp wf-conn-helper-facts(5)* **by** *metis*
finally show $\text{all-subformula-st test-symb } (F\text{And } \varphi \psi)$
 $\longleftrightarrow (\text{test-symb } (F\text{And } \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
by *simp*

have $\text{all-subformula-st test-symb } (F\text{Or } \varphi \psi) \longleftrightarrow \text{all-subformula-st test-symb } (\text{conn } C\text{Or } [\varphi, \psi])$
by *auto*
moreover have $\dots \longleftrightarrow$
 $(\text{test-symb } (\text{conn } C\text{Or } [\varphi, \psi]) \wedge (\forall \xi \in \text{set } [\varphi, \psi]. \text{all-subformula-st test-symb } \xi))$
using *all-subformula-st-decomp wf-conn-helper-facts(6)* **by** *metis*
finally show $\text{all-subformula-st test-symb } (F\text{Or } \varphi \psi)$
 $\longleftrightarrow (\text{test-symb } (F\text{Or } \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
by *simp*

have $\text{all-subformula-st test-symb } (F\text{Eq } \varphi \psi) \longleftrightarrow \text{all-subformula-st test-symb } (\text{conn } C\text{Eq } [\varphi, \psi])$
by *auto*
moreover have \dots
 $\longleftrightarrow (\text{test-symb } (\text{conn } C\text{Eq } [\varphi, \psi]) \wedge (\forall \xi \in \text{set } [\varphi, \psi]. \text{all-subformula-st test-symb } \xi))$
using *all-subformula-st-decomp wf-conn-helper-facts(8)* **by** *metis*
finally show $\text{all-subformula-st test-symb } (F\text{Eq } \varphi \psi)$
 $\longleftrightarrow (\text{test-symb } (F\text{Eq } \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
by *simp*

have $\text{all-subformula-st test-symb } (F\text{Imp } \varphi \psi) \longleftrightarrow \text{all-subformula-st test-symb } (\text{conn } C\text{Imp } [\varphi, \psi])$
by *auto*
moreover have \dots
 $\longleftrightarrow (\text{test-symb } (\text{conn } C\text{Imp } [\varphi, \psi]) \wedge (\forall \xi \in \text{set } [\varphi, \psi]. \text{all-subformula-st test-symb } \xi))$
using *all-subformula-st-decomp wf-conn-helper-facts(7)* **by** *metis*
finally show $\text{all-subformula-st test-symb } (F\text{Imp } \varphi \psi)$
 $\longleftrightarrow (\text{test-symb } (F\text{Imp } \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
by *simp*

have $\text{all-subformula-st test-symb } (F\text{Not } \varphi) \longleftrightarrow \text{all-subformula-st test-symb } (\text{conn } C\text{Not } [\varphi])$
by *auto*
moreover have $\dots = (\text{test-symb } (\text{conn } C\text{Not } [\varphi]) \wedge (\forall \xi \in \text{set } [\varphi]. \text{all-subformula-st test-symb } \xi))$
using *all-subformula-st-decomp wf-conn-helper-facts(1)* **by** *metis*
finally show $\text{all-subformula-st test-symb } (F\text{Not } \varphi)$
 $\longleftrightarrow (\text{test-symb } (F\text{Not } \varphi) \wedge \text{all-subformula-st test-symb } \varphi)$ **by** *simp*
qed

As *all-subformula-st* tests recursively, the function is true on every subformula.

lemma *subformula-all-subformula-st*:

$\psi \preceq \varphi \implies \text{all-subformula-st test-symb } \varphi \implies \text{all-subformula-st test-symb } \psi$
by (*induct rule: subformula.induct, auto simp add: all-subformula-st-decomp*)

The following theorem *no-test-symb-step-exists* shows the link between the *test-symb* function and the corresponding rewrite relation *r*: if we assume that if every time *test-symb* is true, then a *r* can be applied, finally as long as $\neg \text{all-subformula-st test-symb } \varphi$, then something can be rewritten in φ .

lemma *no-test-symb-step-exists*:

```

fixes r:: 'v propo  $\Rightarrow$  'v propo  $\Rightarrow$  bool and test-symb:: 'v propo  $\Rightarrow$  bool and x:: 'v
and  $\varphi$  :: 'v propo
assumes test-symb-false-nullary:  $\forall x. \text{test-symb } FF \wedge \text{test-symb } FT \wedge \text{test-symb } (FVar\ x)$ 
and  $\forall \varphi'. \varphi' \preceq \varphi \longrightarrow (\neg \text{test-symb } \varphi') \longrightarrow (\exists \psi. r\ \varphi'\ \psi)$  and
 $\neg \text{all-subformula-st test-symb } \varphi$ 
shows  $(\exists \psi\ \psi'. \psi \preceq \varphi \wedge r\ \psi\ \psi')$ 
using assms
proof (induct  $\varphi$  rule: propo-induct-arity)
case (nullary  $\varphi\ x$ )
thus  $\exists \psi\ \psi'. \psi \preceq \varphi \wedge r\ \psi\ \psi'$ 
using wf-conn-nullary test-symb-false-nullary by fastforce
next
case (unary  $\varphi$ ) note IH = this(1)[OF this(2)] and r = this(2) and nst = this(3) and subf =
this(4)
from r IH nst have H:  $\neg \text{all-subformula-st test-symb } \varphi \implies \exists \psi. \psi \preceq \varphi \wedge (\exists \psi'. r\ \psi\ \psi')$ 
by (metis subformula-in-subformula-not subformula-refl subformula-trans)
{
assume n:  $\neg \text{test-symb } (FNot\ \varphi)$ 
obtain  $\psi$  where  $r\ (FNot\ \varphi)\ \psi$  using subformula-refl r n nst by blast
moreover have  $FNot\ \varphi \preceq FNot\ \varphi$  using subformula-refl by auto
ultimately have  $\exists \psi\ \psi'. \psi \preceq FNot\ \varphi \wedge r\ \psi\ \psi'$  by metis
}
moreover {
assume n:  $\text{test-symb } (FNot\ \varphi)$ 
hence  $\neg \text{all-subformula-st test-symb } \varphi$ 
using all-subformula-st-decomp-explicit(3) nst subf by blast
hence  $\exists \psi\ \psi'. \psi \preceq FNot\ \varphi \wedge r\ \psi\ \psi'$ 
using H subformula-in-subformula-not subformula-refl subformula-trans by blast
}
ultimately show  $\exists \psi\ \psi'. \psi \preceq FNot\ \varphi \wedge r\ \psi\ \psi'$  by blast
next
case (binary  $\varphi\ \varphi_1\ \varphi_2$ )
note  $IH\ \varphi_1-0 = \text{this}(1)[OF\ \text{this}(4)]$  and  $IH\ \varphi_2-0 = \text{this}(2)[OF\ \text{this}(4)]$  and r = this(4)
and  $\varphi = \text{this}(3)$  and le = this(5) and nst = this(6)

obtain c :: 'v connective where
c:  $(c = CAnd \vee c = COr \vee c = CImp \vee c = CEq) \wedge \text{conn } c\ [\varphi_1, \varphi_2] = \varphi$ 
using  $\varphi$  by fastforce

hence corr: wf-conn c  $[\varphi_1, \varphi_2]$  using wf-conn.simps unfolding binary-connectives-def by auto
have inc:  $\varphi_1 \preceq \varphi\ \varphi_2 \preceq \varphi$  using binary-connectives-def c subformula-in-binary-conn by blast+
from r IH $\varphi_1-0$  have IH $\varphi_1$ :  $\neg \text{all-subformula-st test-symb } \varphi_1 \implies \exists \psi\ \psi'. \psi \preceq \varphi_1 \wedge r\ \psi\ \psi'$ 
using inc(1) subformula-trans le by blast
from r IH $\varphi_2-0$  have IH $\varphi_2$ :  $\neg \text{all-subformula-st test-symb } \varphi_2 \implies \exists \psi. \psi \preceq \varphi_2 \wedge (\exists \psi'. r\ \psi\ \psi')$ 
using inc(2) subformula-trans le by blast
have cases:  $\neg \text{test-symb } \varphi \vee \neg \text{all-subformula-st test-symb } \varphi_1 \vee \neg \text{all-subformula-st test-symb } \varphi_2$ 
using c nst by auto
show  $\exists \psi\ \psi'. \psi \preceq \varphi \wedge r\ \psi\ \psi'$ 
using IH $\varphi_1$  IH $\varphi_2$  subformula-trans inc subformula-refl cases le by blast
qed

```

7.2 Invariant conservation

If two rewrite relation are independant (or at least independant enough), then the property characterizing the first relation *all-subformula-st test-symb* remains true. The next show the

same property, with changes in the assumptions.

The assumption $\forall \varphi' \psi. \varphi' \preceq \Phi \longrightarrow r \varphi' \psi \longrightarrow \text{all-subformula-st test-symb } \varphi' \longrightarrow \text{all-subformula-st test-symb } \psi$ means that rewriting with r does not mess up the property we want to preserve locally.

The previous assumption is not enough to go from r to *propo-rew-step* r : we have to add the assumption that rewriting inside does not mess up the term: $\forall c \xi \varphi \xi' \varphi'. \varphi \preceq \Phi \longrightarrow \text{propo-rew-step } r \varphi \varphi' \longrightarrow \text{wf-conn } c (\xi @ \varphi \# \xi') \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi \# \xi')) \longrightarrow \text{test-symb } \varphi' \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$

7.2.1 Invariant while lifting of the rewriting relation

The condition $\varphi \preceq \Phi$ (that will be used with $\Phi = \varphi$ most of the time) is here to ensure that the recursive conditions on Φ will moreover hold for the subterm we are rewriting. For example if there is no equivalence symbol in Φ , we do not have to care about equivalence symbols in the two previous assumptions.

lemma *propo-rew-step-inv-stay*:

```

fixes  $r :: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$  and  $\text{test-symb} :: 'v \text{ propo} \Rightarrow \text{bool}$  and  $x :: 'v$ 
and  $\varphi \psi \Phi :: 'v \text{ propo}$ 
assumes  $H: \forall \varphi' \psi. \varphi' \preceq \Phi \longrightarrow r \varphi' \psi \longrightarrow \text{all-subformula-st test-symb } \varphi'$ 
 $\longrightarrow \text{all-subformula-st test-symb } \psi$ 
and  $H': \forall (c :: 'v \text{ connective}) \xi \varphi \xi' \varphi'. \varphi \preceq \Phi \longrightarrow \text{propo-rew-step } r \varphi \varphi'$ 
 $\longrightarrow \text{wf-conn } c (\xi @ \varphi \# \xi') \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi \# \xi')) \longrightarrow \text{test-symb } \varphi'$ 
 $\longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$  and
 $\text{propo-rew-step } r \varphi \psi$  and
 $\varphi \preceq \Phi$  and
 $\text{all-subformula-st test-symb } \varphi$ 
shows  $\text{all-subformula-st test-symb } \psi$ 
using assms(3-5)
proof (induct rule: propo-rew-step.induct)
case global-rel
thus ?case using  $H$  by simp
next
case (propo-rew-one-step-lift  $\varphi \varphi' c \xi \xi'$ )
note  $\text{rel} = \text{this}(1)$  and  $\varphi = \text{this}(2)$  and  $\text{corr} = \text{this}(3)$  and  $\Phi = \text{this}(4)$  and  $\text{nst} = \text{this}(5)$ 
have  $\text{sq}: \varphi \preceq \Phi$ 
using  $\Phi \text{ corr subformula-into-subformula subformula-refl subformula-trans}$ 
by (metis in-set-conv-decomp)
from  $\text{corr}$  have  $\forall \psi. \psi \in \text{set } (\xi @ \varphi \# \xi') \longrightarrow \text{all-subformula-st test-symb } \psi$ 
using  $\text{all-subformula-st-decomp nst}$  by blast
hence *:  $\forall \psi. \psi \in \text{set } (\xi @ \varphi' \# \xi') \longrightarrow \text{all-subformula-st test-symb } \psi$  using  $\varphi \text{ sq}$  by fastforce
hence  $\text{test-symb } \varphi'$  using  $\text{all-subformula-st-test-symb-true-phi}$  by auto
moreover from  $\text{corr nst}$  have  $\text{test-symb } (\text{conn } c (\xi @ \varphi \# \xi'))$ 
using  $\text{all-subformula-st-decomp}$  by blast
ultimately have  $\text{test-symb: test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$  using  $H' \text{ sq corr rel}$  by blast

have  $\text{wf-conn } c (\xi @ \varphi' \# \xi')$ 
by (metis wf-conn-no-arity-change-helper corr wf-conn-no-arity-change)
thus  $\text{all-subformula-st test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$ 
using *  $\text{test-symb}$  by (metis all-subformula-st-decomp)
qed

```

The need for $\varphi \preceq \Phi$ is not always necessary, hence we moreover have a version without inclusion.

lemma *propo-rew-step-inv-stay*:

fixes $r :: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **and** $\text{test-symb} :: 'v \text{ propo} \Rightarrow \text{bool}$ **and** $x :: 'v$

and $\varphi \psi :: 'v \text{ propo}$

assumes

$H: \forall \varphi' \psi. r \varphi' \psi \longrightarrow \text{all-subformula-st test-symb } \varphi' \longrightarrow \text{all-subformula-st test-symb } \psi$ **and**

$H': \forall (c :: 'v \text{ connective}) \xi \varphi \xi' \varphi'. \text{wf-conn } c (\xi @ \varphi \# \xi') \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi \# \xi'))$
 $\longrightarrow \text{test-symb } \varphi' \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$ **and**

$\text{propo-rew-step } r \varphi \psi$ **and**

$\text{all-subformula-st test-symb } \varphi$

shows $\text{all-subformula-st test-symb } \psi$

using *propo-rew-step-inv-stay'*[of $\varphi \ r \ \text{test-symb } \varphi \ \psi$] *assms subformula-refl* **by** *metis*

The lemmas can be lifted to *full* (*propo-rew-step* r) instead of *propo-rew-step*

7.2.2 Invariant after all rewriting

lemma *full-propo-rew-step-inv-stay-with-inc*:

fixes $r :: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **and** $\text{test-symb} :: 'v \text{ propo} \Rightarrow \text{bool}$ **and** $x :: 'v$

and $\varphi \psi :: 'v \text{ propo}$

assumes

$H: \forall \varphi \psi. \text{propo-rew-step } r \varphi \psi \longrightarrow \text{all-subformula-st test-symb } \varphi$
 $\longrightarrow \text{all-subformula-st test-symb } \psi$ **and**

$H': \forall (c :: 'v \text{ connective}) \xi \varphi \xi' \varphi'. \varphi \preceq \Phi \longrightarrow \text{propo-rew-step } r \varphi \varphi'$
 $\longrightarrow \text{wf-conn } c (\xi @ \varphi \# \xi') \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi \# \xi')) \longrightarrow \text{test-symb } \varphi'$
 $\longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$ **and**

$\varphi \preceq \Phi$ **and**

$\text{full: full } (\text{propo-rew-step } r) \varphi \psi$ **and**

$\text{init: all-subformula-st test-symb } \varphi$

shows $\text{all-subformula-st test-symb } \psi$

using *assms unfolding full-def*

proof –

have $\text{rel: } (\text{propo-rew-step } r)^{**} \varphi \psi$

using *full unfolding full-def* **by** *auto*

thus $\text{all-subformula-st test-symb } \psi$

using *init*

proof (*induct rule: rtranclp-induct*)

case *base*

then show $\text{all-subformula-st test-symb } \varphi$ **by** *blast*

next

case (*step* $b \ c$) **note** $\text{star} = \text{this}(1)$ **and** $\text{IH} = \text{this}(3)$ **and** $\text{one} = \text{this}(2)$ **and** $\text{all} = \text{this}(4)$

then have $\text{all-subformula-st test-symb } b$ **by** *metis*

then show $\text{all-subformula-st test-symb } c$ **using** *propo-rew-step-inv-stay'* $H \ H' \ \text{rel one}$ **by** *auto*

qed

qed

lemma *full-propo-rew-step-inv-stay'*:

fixes $r :: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **and** $\text{test-symb} :: 'v \text{ propo} \Rightarrow \text{bool}$ **and** $x :: 'v$

and $\varphi \psi :: 'v \text{ propo}$

assumes

$H: \forall \varphi \psi. \text{propo-rew-step } r \varphi \psi \longrightarrow \text{all-subformula-st test-symb } \varphi$
 $\longrightarrow \text{all-subformula-st test-symb } \psi$ **and**

$H': \forall (c :: 'v \text{ connective}) \xi \varphi \xi' \varphi'. \text{propo-rew-step } r \varphi \varphi' \longrightarrow \text{wf-conn } c (\xi @ \varphi \# \xi')$

$\longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi \# \xi')) \longrightarrow \text{test-symb } \varphi' \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$ **and**

$\text{full: full } (\text{propo-rew-step } r) \varphi \psi$ **and**

$\text{init: all-subformula-st test-symb } \varphi$

shows $\text{all-subformula-st test-symb } \psi$

using *full-propo-rew-step-inv-stay-with-inc*[of *r test-symb* φ] *assms subformula-refl* **by** *metis*

lemma *full-propo-rew-step-inv-stay*:

fixes $r :: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **and** *test-symb* :: $'v \text{ propo} \Rightarrow \text{bool}$ **and** $x :: 'v$

and $\varphi \psi :: 'v \text{ propo}$

assumes

$H: \forall \varphi \psi. r \varphi \psi \longrightarrow \text{all-subformula-st test-symb } \varphi \longrightarrow \text{all-subformula-st test-symb } \psi$ **and**

$H': \forall (c :: 'v \text{ connective}) \xi \varphi \xi' \varphi'. \text{wf-conn } c (\xi @ \varphi \# \xi') \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi \# \xi'))$
 $\longrightarrow \text{test-symb } \varphi' \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$ **and**

full: *full* (*propo-rew-step* r) $\varphi \psi$ **and**

init: *all-subformula-st test-symb* φ

shows *all-subformula-st test-symb* ψ

unfolding *full-def*

proof –

have *rel*: (*propo-rew-step* r)^{**} $\varphi \psi$

using *full* **unfolding** *full-def* **by** *auto*

thus *all-subformula-st test-symb* ψ

using *init*

proof (*induct rule*: *rtranclp-induct*)

case *base*

thus *all-subformula-st test-symb* φ **by** *blast*

next

case (*step* $b \ c$)

note *star* = *this*(1) **and** *IH* = *this*(3) **and** *one* = *this*(2) **and** *all* = *this*(4)

hence *all-subformula-st test-symb* b **by** *metis*

thus *all-subformula-st test-symb* c

using *propo-rew-step-inv-stay subformula-refl* $H \ H'$ *rel one* **by** *auto*

qed

qed

lemma *full-propo-rew-step-inv-stay-conn*:

fixes $r :: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **and** *test-symb* :: $'v \text{ propo} \Rightarrow \text{bool}$ **and** $x :: 'v$

and $\varphi \psi :: 'v \text{ propo}$

assumes

$H: \forall \varphi \psi. r \varphi \psi \longrightarrow \text{all-subformula-st test-symb } \varphi \longrightarrow \text{all-subformula-st test-symb } \psi$ **and**

$H': \forall (c :: 'v \text{ connective}) \ l \ l'. \text{wf-conn } c \ l \longrightarrow \text{wf-conn } c \ l'$
 $\longrightarrow (\text{test-symb } (\text{conn } c \ l) \longleftrightarrow \text{test-symb } (\text{conn } c \ l'))$ **and**

full: *full* (*propo-rew-step* r) $\varphi \psi$ **and**

init: *all-subformula-st test-symb* φ

shows *all-subformula-st test-symb* ψ

proof –

have $\bigwedge (c :: 'v \text{ connective}) \xi \varphi \xi' \varphi'. \text{wf-conn } c (\xi @ \varphi \# \xi')$

$\implies \text{test-symb } (\text{conn } c (\xi @ \varphi \# \xi')) \implies \text{test-symb } \varphi' \implies \text{test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$

using H' **by** (*metis wf-conn-no-arity-change-helper wf-conn-no-arity-change*)

thus *all-subformula-st test-symb* ψ

using H *full init full-propo-rew-step-inv-stay* **by** *blast*

qed

end

theory *Prop-Normalisation*

imports *Main Prop-Logic Prop-Abstract-Transformation*

begin

Given the previous definition about abstract rewriting and theorem about them, we now have the detailed rule making the transformation into CNF/DNF.

8 Rewrite Rules

The idea of Christoph Weidenbach's book is to remove gradually the operators: first equivalencies, then implication, after that the unused true/false and finally the reorganizing the or/and. We will prove each transformation separately.

8.1 Elimination of the equivalences

The first transformation consists in removing every equivalence symbol.

inductive *elim-equiv* :: 'v propo \Rightarrow 'v propo \Rightarrow bool **where**
elim-equiv[simp]: *elim-equiv* (FEq φ ψ) (FAnd (FImp φ ψ) (FImp ψ φ))

lemma *elim-equiv-transformation-consistent*:
 $A \models \text{FEq } \varphi \ \psi \longleftrightarrow A \models \text{FAnd } (\text{FImp } \varphi \ \psi) \ (\text{FImp } \psi \ \varphi)$
by *auto*

lemma *elim-equiv-explicit*: *elim-equiv* $\varphi \ \psi \implies \forall A. A \models \varphi \longleftrightarrow A \models \psi$
by (*induct* rule: *elim-equiv.induct*, *auto*)

lemma *elim-equiv-consistent*: *preserves-un-sat elim-equiv*
unfolding *preserves-un-sat-def* **by** (*simp* add: *elim-equiv-explicit*)

lemma *elimEquiv-lifted-consistent*:
preserves-un-sat (full (propo-rew-step elim-equiv))
by (*simp* add: *elim-equiv-consistent*)

This function ensures that there is no equivalencies left in the formula tested by *no-equiv-symb*.

fun *no-equiv-symb* :: 'v propo \Rightarrow bool **where**
no-equiv-symb (FEq -) = False |
no-equiv-symb - = True

Given the definition of *no-equiv-symb*, it does not depend on the formula, but only on the connective used.

lemma *no-equiv-symb-conn-characterization*[simp]:
fixes $c :: 'v \text{ connective}$ **and** $l :: 'v \text{ propo list}$
assumes *wf*: *wf-conn* $c \ l$
shows *no-equiv-symb* (*conn* $c \ l$) $\longleftrightarrow c \neq \text{CEq}$
by (*metis* *connective.distinct*(13,25,35,43) *wf no-equiv-symb.elims*(3) *no-equiv-symb.simps*(1)
wf-conn.cases wf-conn-list(6))

definition *no-equiv* **where** *no-equiv* = *all-subformula-st no-equiv-symb*

lemma *no-equiv-eq*[simp]:
fixes $\varphi \ \psi :: 'v \text{ propo}$
shows
 $\neg \text{no-equiv } (\text{FEq } \varphi \ \psi)$
no-equiv FT
no-equiv FF
using *no-equiv-symb.simps*(1) *all-subformula-st-test-symb-true-phi* **unfolding** *no-equiv-def* **by** *auto*

The following lemma helps to reconstruct *no-equiv* expressions: this representation is easier to use than the set definition.

lemma *all-subformula-st-decomp-explicit-no-equiv*[iff]:

fixes $\varphi \ \psi :: 'v \text{ propo}$

shows

$\text{no-equiv } (FNot \ \varphi) \longleftrightarrow \text{no-equiv } \varphi$
 $\text{no-equiv } (FAnd \ \varphi \ \psi) \longleftrightarrow (\text{no-equiv } \varphi \wedge \text{no-equiv } \psi)$
 $\text{no-equiv } (FOr \ \varphi \ \psi) \longleftrightarrow (\text{no-equiv } \varphi \wedge \text{no-equiv } \psi)$
 $\text{no-equiv } (FImp \ \varphi \ \psi) \longleftrightarrow (\text{no-equiv } \varphi \wedge \text{no-equiv } \psi)$
by (*auto simp add: no-equiv-def*)

A theorem to show the link between the rewrite relation *elim-equiv* and the function *no-equiv-symb*. This theorem is one of the assumption we need to characterize the transformation.

lemma *no-equiv-elim-equiv-step*:

fixes $\varphi :: 'v \text{ propo}$

assumes *no-equiv*: $\neg \text{no-equiv } \varphi$

shows $\exists \psi \ \psi'. \ \psi \preceq \varphi \wedge \text{elim-equiv } \psi \ \psi'$

proof –

have *test-symb-false-nullary*:

$\forall x::'v. \text{no-equiv-symb } FF \wedge \text{no-equiv-symb } FT \wedge \text{no-equiv-symb } (FVar \ x)$

unfolding *no-equiv-def* **by** *auto*

moreover {

fix $c::'v \text{ connective}$ **and** $l::'v \text{ propo list}$ **and** $\psi::'v \text{ propo}$

assume *a1*: $\text{elim-equiv } (\text{conn } c \ l) \ \psi$

have $\bigwedge p \ \text{pa}. \neg \text{elim-equiv } (p::'v \text{ propo}) \ \text{pa} \vee \neg \text{no-equiv-symb } p$

using *elim-equiv.cases no-equiv-symb.simps(1)* **by** *blast*

hence $\text{elim-equiv } (\text{conn } c \ l) \ \psi \implies \neg \text{no-equiv-symb } (\text{conn } c \ l)$ **using** *a1* **by** *metis*

}

moreover **have** $H': \forall \psi. \neg \text{elim-equiv } FT \ \psi \ \forall \psi. \neg \text{elim-equiv } FF \ \psi \ \forall \psi \ x. \neg \text{elim-equiv } (FVar \ x) \ \psi$

using *elim-equiv.cases* **by** *auto*

moreover **have** $\bigwedge \varphi. \neg \text{no-equiv-symb } \varphi \implies \exists \psi. \text{elim-equiv } \varphi \ \psi$

by (*case-tac* φ , *auto simp add: elim-equiv.simps*)

hence $\bigwedge \varphi'. \ \varphi' \preceq \varphi \implies \neg \text{no-equiv-symb } \varphi' \implies \exists \psi. \text{elim-equiv } \varphi' \ \psi$ **by** *force*

ultimately show *?thesis*

using *no-test-symb-step-exists no-equiv test-symb-false-nullary unfolding no-equiv-def* **by** *blast*

qed

Given all the previous theorem and the characterization, once we have rewritten everything, there is no equivalence symbol any more.

lemma *no-equiv-full-propo-rew-step-elim-equiv*:

full (*propo-rew-step elim-equiv*) $\varphi \ \psi \implies \text{no-equiv } \psi$

using *full-propo-rew-step-subformula no-equiv-elim-equiv-step* **by** *blast*

8.2 Eliminate Implication

After that, we can eliminate the implication symbols.

inductive *elim-imp* $:: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **where**

[*simp*]: *elim-imp* (*FImp* $\varphi \ \psi$) (*FOr* (*FNot* φ) ψ)

lemma *elim-imp-transformation-consistent*:

$A \models FImp \ \varphi \ \psi \longleftrightarrow A \models FOr \ (FNot \ \varphi) \ \psi$

by *auto*

lemma *elim-imp-explicit*: $\text{elim-imp } \varphi \ \psi \implies \forall A. \ A \models \varphi \longleftrightarrow A \models \psi$

by (*induct* $\varphi \ \psi$ *rule: elim-imp.induct, auto*)

lemma *elim-imp-consistent: preserves-un-sat elim-imp*
unfolding *preserves-un-sat-def* **by** (*simp add: elim-imp-explicit*)

lemma *elim-imp-lifted-consistent:*
preserves-un-sat (full (propo-rew-step elim-imp))
by (*simp add: elim-imp-consistent*)

fun *no-imp-symb* **where**
no-imp-symb (FImp -) = False |
no-imp-symb - = True

lemma *no-imp-symb-conn-characterization:*
wf-conn c l \implies no-imp-symb (conn c l) \longleftrightarrow c \neq CImp
by (*induction rule: wf-conn-induct*) *auto*

definition *no-imp* **where** *no-imp \equiv all-subformula-st no-imp-symb*
declare *no-imp-def[simp]*

lemma *no-imp-Imp[simp]:*
 \neg *no-imp (FImp φ ψ)*
no-imp FT
no-imp FF
unfolding *no-imp-def* **by** *auto*

lemma *all-subformula-st-decomp-explicit-imp[simp]:*
fixes $\varphi \psi :: 'v$ *propo*
shows
no-imp (FNot φ) \longleftrightarrow no-imp φ
no-imp (FAnd $\varphi \psi$) \longleftrightarrow (no-imp $\varphi \wedge$ no-imp ψ)
no-imp (FOr $\varphi \psi$) \longleftrightarrow (no-imp $\varphi \wedge$ no-imp ψ)
by *auto*

Invariant of the *elim-imp* transformation

lemma *elim-imp-no-equiv:*
elim-imp $\varphi \psi \implies$ no-equiv $\varphi \implies$ no-equiv ψ
by (*induct $\varphi \psi$ rule: elim-imp.induct, auto*)

lemma *elim-imp-inv:*
fixes $\varphi \psi :: 'v$ *propo*
assumes *full (propo-rew-step elim-imp) $\varphi \psi$*
and *no-equiv φ*
shows *no-equiv ψ*
using *full-propo-rew-step-inv-stay-conn[of elim-imp no-equiv-symb $\varphi \psi$] assms elim-imp-no-equiv*
no-equiv-symb-conn-characterization **unfolding** *no-equiv-def* **by** *metis*

lemma *no-no-imp-elim-imp-step-exists:*
fixes $\varphi :: 'v$ *propo*
assumes *no-equiv: \neg no-imp φ*
shows $\exists \psi \psi'. \psi \preceq \varphi \wedge$ *elim-imp $\psi \psi'$*

proof –

have *test-symb-false-nullary: $\forall x. \text{no-imp-symb } FF \wedge \text{no-imp-symb } FT \wedge \text{no-imp-symb } (FVar (x:: 'v))$*
by *auto*
moreover {

```

fix c:: 'v connective and l :: 'v propo list and  $\psi$  :: 'v propo
have H: elim-imp (conn c l)  $\psi \implies \neg$ no-imp-symb (conn c l)
  by (auto elim: elim-imp.cases)
}
moreover
  have H':  $\forall \psi. \neg$ elim-imp FT  $\psi \forall \psi. \neg$ elim-imp FF  $\psi \forall \psi x. \neg$ elim-imp (FVar x)  $\psi$ 
    by (auto elim: elim-imp.cases)+
  moreover have  $\bigwedge \varphi. \neg$ no-imp-symb  $\varphi \implies \exists \psi. \text{elim-imp } \varphi \psi$ 
    apply (case-tac  $\varphi$ ) using elim-imp.simps by force+
  hence  $(\bigwedge \varphi'. \varphi' \preceq \varphi \implies \neg$ no-imp-symb  $\varphi' \implies \exists \psi. \text{elim-imp } \varphi' \psi)$  by force
  ultimately show ?thesis
    using no-test-symb-step-exists no-equiv test-symb-false-nullary unfolding no-imp-def by blast
qed

```

lemma *no-imp-full-propo-rew-step-elim-imp: full (propo-rew-step elim-imp) $\varphi \psi \implies$ no-imp ψ*
 using full-propo-rew-step-subformula no-no-imp-elim-imp-step-exists by blast

8.3 Eliminate all the True and False in the formula

Contrary to the book, we have to give the transformation and the “commutative” transformation. The latter is implicit in the book.

inductive *elimTB* **where**

ElimTB1: elimTB (FAnd φ FT) φ |

ElimTB1': elimTB (FAnd FT φ) φ |

ElimTB2: elimTB (FAnd φ FF) FF |

ElimTB2': elimTB (FAnd FF φ) FF |

ElimTB3: elimTB (FOr φ FT) FT |

ElimTB3': elimTB (FOr FT φ) FT |

ElimTB4: elimTB (FOr φ FF) φ |

ElimTB4': elimTB (FOr FF φ) φ |

ElimTB5: elimTB (FNot FT) FF |

ElimTB6: elimTB (FNot FF) FT

lemma *elimTB-consistent: preserves-un-sat elimTB*

proof –

```

{
  fix  $\varphi \psi$ :: 'b propo
  have elimTB  $\varphi \psi \implies \forall A. A \models \varphi \longleftrightarrow A \models \psi$  by (induct-tac rule: elimTB.inducts) auto
}
thus ?thesis using preserves-un-sat-def by auto
qed

```

inductive *no-T-F-symb* :: 'v propo \Rightarrow bool **where**

no-T-F-symb-comp: $c \neq CF \implies c \neq CT \implies \text{wf-conn } c \ l \implies (\forall \varphi \in \text{set } l. \varphi \neq FT \wedge \varphi \neq FF)$
 \implies no-T-F-symb (conn c l)

lemma *wf-conn-no-T-F-symb-iff[simp]:*

$\text{wf-conn } c \ \psi s \implies \text{no-T-F-symb (conn c } \psi s) \longleftrightarrow (c \neq CF \wedge c \neq CT \wedge (\forall \psi \in \text{set } \psi s. \psi \neq FF \wedge \psi \neq$

```

FT))
unfolding no-T-F-symb.simps apply (cases c)
  using wf-conn-list(1) apply fastforce
  using wf-conn-list(2) apply fastforce
  using wf-conn-list(3) apply fastforce
  apply (metis (no-types, hide-lams) conn-inj connective.distinct(5,17))
  using conn-inj apply blast+
done

lemma wf-conn-no-T-F-symb-iff-explicit[simp]:
no-T-F-symb (FAnd  $\varphi$   $\psi$ )  $\longleftrightarrow (\forall \chi \in \text{set } [\varphi, \psi]. \chi \neq FF \wedge \chi \neq FT)$ 
no-T-F-symb (FOr  $\varphi$   $\psi$ )  $\longleftrightarrow (\forall \chi \in \text{set } [\varphi, \psi]. \chi \neq FF \wedge \chi \neq FT)$ 
no-T-F-symb (FEq  $\varphi$   $\psi$ )  $\longleftrightarrow (\forall \chi \in \text{set } [\varphi, \psi]. \chi \neq FF \wedge \chi \neq FT)$ 
no-T-F-symb (FImp  $\varphi$   $\psi$ )  $\longleftrightarrow (\forall \chi \in \text{set } [\varphi, \psi]. \chi \neq FF \wedge \chi \neq FT)$ 
  apply (metis conn.simps(36) conn.simps(37) conn.simps(5) propo.distinct(19)
    wf-conn-helper-facts(5) wf-conn-no-T-F-symb-iff)
  apply (metis conn.simps(36) conn.simps(37) conn.simps(6) propo.distinct(22)
    wf-conn-helper-facts(6) wf-conn-no-T-F-symb-iff)
  using wf-conn-no-T-F-symb-iff apply fastforce
by (metis conn.simps(36) conn.simps(37) conn.simps(7) propo.distinct(23) wf-conn-helper-facts(7)
  wf-conn-no-T-F-symb-iff)

lemma no-T-F-symb-false[simp]:
fixes c :: 'v connective
shows
   $\neg$ no-T-F-symb (FT :: 'v propo)
   $\neg$ no-T-F-symb (FF :: 'v propo)
  by (metis (no-types) conn.simps(1,2) wf-conn-no-T-F-symb-iff wf-conn-nullary)+

lemma no-T-F-symb-bool[simp]:
fixes x :: 'v
shows no-T-F-symb (FVar x)
using no-T-F-symb-comp wf-conn-nullary by (metis connective.distinct(3, 15) conn.simps(3)
  empty-iff list.set(1))

lemma no-T-F-symb-fnot-imp:
 $\neg$ no-T-F-symb (FNot  $\varphi$ )  $\implies \varphi = FT \vee \varphi = FF$ 
proof (rule ccontr)
  assume n:  $\neg$  no-T-F-symb (FNot  $\varphi$ )
  assume  $\neg (\varphi = FT \vee \varphi = FF)$ 
  hence  $\forall \varphi' \in \text{set } [\varphi]. \varphi' \neq FT \wedge \varphi' \neq FF$  by auto
  moreover have wf-conn CNot  $[\varphi]$  by simp
  ultimately have no-T-F-symb (FNot  $\varphi$ )
    using no-T-F-symb.intros by (metis conn.simps(4) connective.distinct(5,17))
  thus False using n by blast
qed

lemma no-T-F-symb-fnot[simp]:
no-T-F-symb (FNot  $\varphi$ )  $\longleftrightarrow \neg(\varphi = FT \vee \varphi = FF)$ 
using no-T-F-symb.simps no-T-F-symb-fnot-imp by (metis conn-inj-not(2) list.set-intros(1))

```

Actually it is not possible to remove every FT and FF : if the formula is equal to true or false, we can not remove it.

inductive *no-T-F-symb-except-toplevel* **where**
no-T-F-symb-except-toplevel-true[simp]: *no-T-F-symb-except-toplevel* *FT* |
no-T-F-symb-except-toplevel-false[simp]: *no-T-F-symb-except-toplevel* *FF* |
noTrue-no-T-F-symb-except-toplevel[simp]: *no-T-F-symb* $\varphi \implies$ *no-T-F-symb-except-toplevel* φ

lemma *no-T-F-symb-except-toplevel-bool*[simp]:
fixes *x* :: '*v*
shows *no-T-F-symb-except-toplevel* (*FVar* *x*)
by *simp*

lemma *no-T-F-symb-except-toplevel-not-decom*:
 $\varphi \neq FT \implies \varphi \neq FF \implies$ *no-T-F-symb-except-toplevel* (*FNot* φ)
by *simp*

lemma *no-T-F-symb-except-toplevel-bin-decom*:
fixes $\varphi \psi$:: '*v* *propo*
assumes $\varphi \neq FT$ **and** $\varphi \neq FF$ **and** $\psi \neq FT$ **and** $\psi \neq FF$
and *c*: *c* ∈ *binary-connectives*
shows *no-T-F-symb-except-toplevel* (*conn* *c* [φ , ψ])
by (*metis* (*no-types*, *lifting*) *assms* *c* *conn.simps*(4) *list.discI* *noTrue-no-T-F-symb-except-toplevel*
wf-conn-no-T-F-symb-iff *no-T-F-symb-fnot* *set.ConsD* *wf-conn-binary* *wf-conn-helper-facts*(1)
wf-conn-list-decomp(1,2))

lemma *no-T-F-symb-except-toplevel-if-is-a-true-false*:
fixes *l* :: '*v* *propo* *list* **and** *c* :: '*v* *connective*
assumes *corr*: *wf-conn* *c* *l*
and *FT* ∈ *set* *l* ∨ *FF* ∈ *set* *l*
shows \neg *no-T-F-symb-except-toplevel* (*conn* *c* *l*)
by (*metis* *assms* *empty-iff* *no-T-F-symb-except-toplevel.simps* *wf-conn-no-T-F-symb-iff* *set-empty*
wf-conn-list(1,2))

lemma *no-T-F-symb-except-top-level-false-example*[simp]:
fixes $\varphi \psi$:: '*v* *propo*
assumes $\varphi = FT \vee \psi = FT \vee \varphi = FF \vee \psi = FF$
shows
 \neg *no-T-F-symb-except-toplevel* (*FAnd* $\varphi \psi$)
 \neg *no-T-F-symb-except-toplevel* (*FOr* $\varphi \psi$)
 \neg *no-T-F-symb-except-toplevel* (*FImp* $\varphi \psi$)
 \neg *no-T-F-symb-except-toplevel* (*FEq* $\varphi \psi$)
using *assms* *no-T-F-symb-except-toplevel-if-is-a-true-false* **unfolding** *binary-connectives-def*
by (*metis* (*no-types*) *conn.simps*(5–8) *insert-iff* *list.simps*(14–15) *wf-conn-helper-facts*(5–8))+

lemma *no-T-F-symb-except-top-level-false-not*[simp]:
fixes $\varphi \psi$:: '*v* *propo*
assumes $\varphi = FT \vee \varphi = FF$
shows
 \neg *no-T-F-symb-except-toplevel* (*FNot* φ)
by (*simp* *add*: *assms* *no-T-F-symb-except-toplevel.simps*)

This is the local extension of *no-T-F-symb-except-toplevel*.

definition *no-T-F-except-top-level* **where**

no-T-F-except-top-level \equiv *all-subformula-st no-T-F-symb-except-toplevel*

This is another property we will use. While this version might seem to be the one we want to prove, it is not since *FT* can not be reduced.

definition *no-T-F* **where**

no-T-F \equiv *all-subformula-st no-T-F-symb*

lemma *no-T-F-except-top-level-false*:

fixes *l* :: 'v propo list **and** *c* :: 'v connective

assumes *wf-conn c l*

and *FT* \in *set l* \vee *FF* \in *set l*

shows \neg *no-T-F-except-top-level* (*conn c l*)

by (*simp add: all-subformula-st-decomp assms no-T-F-except-top-level-def no-T-F-symb-except-toplevel-if-is-a-true-false*)

lemma *no-T-F-except-top-level-false-example*[*simp*]:

fixes $\varphi \psi$:: 'v propo

assumes $\varphi = FT \vee \psi = FT \vee \varphi = FF \vee \psi = FF$

shows

\neg *no-T-F-except-top-level* (*FAnd* $\varphi \psi$)

\neg *no-T-F-except-top-level* (*FOr* $\varphi \psi$)

\neg *no-T-F-except-top-level* (*FEq* $\varphi \psi$)

\neg *no-T-F-except-top-level* (*FImp* $\varphi \psi$)

by (*metis all-subformula-st-test-symb-true-phi assms no-T-F-except-top-level-def no-T-F-symb-except-top-level-false-example*)+

lemma *no-T-F-symb-except-toplevel-no-T-F-symb*:

no-T-F-symb-except-toplevel $\varphi \implies \varphi \neq FF \implies \varphi \neq FT \implies$ *no-T-F-symb* φ

by (*induct rule: no-T-F-symb-except-toplevel.induct, auto*)

The two following lemmas give the precise link between the two definitions.

lemma *no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb*:

no-T-F-except-top-level $\varphi \implies \varphi \neq FF \implies \varphi \neq FT \implies$ *no-T-F* φ

unfolding *no-T-F-except-top-level-def no-T-F-def* **apply** (*induct* φ)

using *no-T-F-symb-fnot* **by** *fastforce*+

lemma *no-T-F-no-T-F-except-top-level*:

no-T-F $\varphi \implies$ *no-T-F-except-top-level* φ

unfolding *no-T-F-except-top-level-def no-T-F-def*

unfolding *all-subformula-st-def* **by** *auto*

lemma *no-T-F-except-top-level-simp*[*simp*]: *no-T-F-except-top-level* *FF* *no-T-F-except-top-level* *FT*

unfolding *no-T-F-except-top-level-def* **by** *auto*

lemma *no-T-F-no-T-F-except-top-level'*[*simp*]:

no-T-F-except-top-level $\varphi \longleftrightarrow (\varphi = FF \vee \varphi = FT \vee$ *no-T-F* $\varphi)$

apply *auto*

using *no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb no-T-F-no-T-F-except-top-level*

by *blast*+

lemma *no-T-F-bin-decomp*[*simp*]:

assumes *c*: *c* \in *binary-connectives*

shows $\text{no-T-F } (\text{conn } c \ [\varphi, \psi]) \longleftrightarrow (\text{no-T-F } \varphi \wedge \text{no-T-F } \psi)$
proof –
have $\text{wf: wf-conn } c \ [\varphi, \psi]$ **using** c **by** *auto*
hence $\text{no-T-F } (\text{conn } c \ [\varphi, \psi]) \longleftrightarrow (\text{no-T-F-symb } (\text{conn } c \ [\varphi, \psi]) \wedge \text{no-T-F } \varphi \wedge \text{no-T-F } \psi)$
by (*simp add: all-subformula-st-decomp no-T-F-def*)
thus $\text{no-T-F } (\text{conn } c \ [\varphi, \psi]) \longleftrightarrow (\text{no-T-F } \varphi \wedge \text{no-T-F } \psi)$
using c *wf all-subformula-st-decomp list.discI no-T-F-def no-T-F-symb-except-toplevel-bin-decom*
 $\text{no-T-F-symb-except-toplevel-no-T-F-symb no-T-F-symb-false(1,2) wf-conn-helper-facts(2,3)}$
 wf-conn-list(1,2) **by** *metis*
qed

lemma *no-T-F-bin-decomp-expanded[simp]:*
assumes $c: c = CAnd \vee c = COr \vee c = CEq \vee c = CImp$
shows $\text{no-T-F } (\text{conn } c \ [\varphi, \psi]) \longleftrightarrow (\text{no-T-F } \varphi \wedge \text{no-T-F } \psi)$
using *no-T-F-bin-decomp assms unfolding binary-connectives-def* **by** *blast*

lemma *no-T-F-comp-expanded-explicit[simp]:*
fixes $\varphi \ \psi :: 'v \text{ propo}$
shows
 $\text{no-T-F } (FAnd \ \varphi \ \psi) \longleftrightarrow (\text{no-T-F } \varphi \wedge \text{no-T-F } \psi)$
 $\text{no-T-F } (FOr \ \varphi \ \psi) \longleftrightarrow (\text{no-T-F } \varphi \wedge \text{no-T-F } \psi)$
 $\text{no-T-F } (FEq \ \varphi \ \psi) \longleftrightarrow (\text{no-T-F } \varphi \wedge \text{no-T-F } \psi)$
 $\text{no-T-F } (FImp \ \varphi \ \psi) \longleftrightarrow (\text{no-T-F } \varphi \wedge \text{no-T-F } \psi)$
using *assms conn.simps(5-8) no-T-F-bin-decomp-expanded* **by** (*metis (no-types)+*)

lemma *no-T-F-comp-not[simp]:*
fixes $\varphi \ \psi :: 'v \text{ propo}$
shows $\text{no-T-F } (FNot \ \varphi) \longleftrightarrow \text{no-T-F } \varphi$
by (*metis all-subformula-st-decomp-explicit(3) all-subformula-st-test-symb-true-phi no-T-F-def*
 $\text{no-T-F-symb-false(1,2) no-T-F-symb-fnot-imp}$)

lemma *no-T-F-decomp:*
fixes $\varphi \ \psi :: 'v \text{ propo}$
assumes $\varphi: \text{no-T-F } (FAnd \ \varphi \ \psi) \vee \text{no-T-F } (FOr \ \varphi \ \psi) \vee \text{no-T-F } (FEq \ \varphi \ \psi) \vee \text{no-T-F } (FImp \ \varphi \ \psi)$
shows $\text{no-T-F } \psi$ **and** $\text{no-T-F } \varphi$
using *assms* **by** *auto*

lemma *no-T-F-decomp-not:*
fixes $\varphi :: 'v \text{ propo}$
assumes $\varphi: \text{no-T-F } (FNot \ \varphi)$
shows $\text{no-T-F } \varphi$
using *assms* **by** *auto*

lemma *no-T-F-symb-except-toplevel-step-exists:*
fixes $\varphi \ \psi :: 'v \text{ propo}$
assumes $\text{no-equiv } \varphi$ **and** $\text{no-imp } \varphi$
shows $\psi \preceq \varphi \implies \neg \text{no-T-F-symb-except-toplevel } \psi \implies \exists \psi'. \text{elimTB } \psi \ \psi'$
proof (*induct ψ rule: propo-induct-arity*)
case (*nullary $\varphi' \ x$*)
hence *False* **using** *no-T-F-symb-except-toplevel-true no-T-F-symb-except-toplevel-false* **by** *auto*
thus *?case* **by** *blast*
next
case (*unary ψ*)
hence $\psi = FF \vee \psi = FT$ **using** *no-T-F-symb-except-toplevel-not-decom* **by** *blast*

```

  thus ?case using ElimTB5 ElimTB6 by blast
next
case (binary  $\varphi'$   $\psi_1$   $\psi_2$ )
note IH1 = this(1) and IH2 = this(2) and  $\varphi' = \text{this}(3)$  and  $F\varphi = \text{this}(4)$  and  $n = \text{this}(5)$ 
{
  assume  $\varphi' = FImp \psi_1 \psi_2 \vee \varphi' = FEq \psi_1 \psi_2$ 
  hence False using  $n F\varphi$  subformula-all-subformula-st assms by (metis (no-types) no-equiv-eq(1)
    no-equiv-def no-imp-Imp(1) no-imp-def)
  hence ?case by blast
}
moreover {
  assume  $\varphi': \varphi' = FAnd \psi_1 \psi_2 \vee \varphi' = FOr \psi_1 \psi_2$ 
  hence  $\psi_1 = FT \vee \psi_2 = FT \vee \psi_1 = FF \vee \psi_2 = FF$ 
  using no-T-F-symb-except-toplevel-bin-decom conn.simps(5,6) n unfolding binary-connectives-def
  by fastforce+
  hence ?case using elimTB.intros  $\varphi'$  by blast
}
ultimately show ?case using  $\varphi'$  by blast
qed

```

lemma no-T-F-except-top-level-rew:

```

fixes  $\varphi :: 'v$  propo
assumes noTB:  $\neg$  no-T-F-except-top-level  $\varphi$  and no-equiv: no-equiv  $\varphi$  and no-imp: no-imp  $\varphi$ 
shows  $\exists \psi \psi'. \psi \preceq \varphi \wedge \text{elimTB } \psi \psi'$ 

```

proof –

```

have test-symb-false-nullary:  $\forall x. \text{no-T-F-symb-except-toplevel } (FF :: 'v \text{ propo})$ 
   $\wedge \text{no-T-F-symb-except-toplevel } FT \wedge \text{no-T-F-symb-except-toplevel } (FVar (x :: 'v))$  by auto

```

```

moreover {
  fix  $c :: 'v$  connective and  $l :: 'v$  propo list and  $\psi :: 'v$  propo
  have  $H: \text{elimTB } (\text{conn } c \ l) \ \psi \implies \neg \text{no-T-F-symb-except-toplevel } (\text{conn } c \ l)$ 
  by (case-tac (conn c l) rule: elimTB.cases, auto)
}

```

```

moreover {
  fix  $x :: 'v$ 
  have  $H': \text{no-T-F-except-top-level } FT \ \text{no-T-F-except-top-level } FF$ 
     $\text{no-T-F-except-top-level } (FVar \ x)$ 
  by (auto simp add: no-T-F-except-top-level-def test-symb-false-nullary)
}

```

```

moreover {
  fix  $\psi$ 
  have  $\psi \preceq \varphi \implies \neg \text{no-T-F-symb-except-toplevel } \psi \implies \exists \psi'. \text{elimTB } \psi \psi'$ 
  using no-T-F-symb-except-toplevel-step-exists no-equiv no-imp by auto
}

```

ultimately show ?thesis

```

using no-test-symb-step-exists noTB unfolding no-T-F-except-top-level-def by blast

```

qed

lemma elimTB-inv:

```

fixes  $\varphi \ \psi :: 'v$  propo
assumes full (propo-rew-step elimTB)  $\varphi \ \psi$ 
and no-equiv  $\varphi$  and no-imp  $\varphi$ 
shows no-equiv  $\psi$  and no-imp  $\psi$ 

```

proof –

```

{

```

```

fix  $\varphi \psi :: 'v \text{ propo}$ 
have  $H: \text{elimTB } \varphi \psi \implies \text{no-equiv } \varphi \implies \text{no-equiv } \psi$ 
  by (induct  $\varphi \psi$  rule:  $\text{elimTB.induct}$ , auto)
}
thus  $\text{no-equiv } \psi$ 
  using  $\text{full-propo-rew-step-inv-stay-conn[of elimTB no-equiv-symb } \varphi \psi]$ 
   $\text{no-equiv-symb-conn-characterization assms unfolding no-equiv-def by metis}$ 
next
{
  fix  $\varphi \psi :: 'v \text{ propo}$ 
  have  $H: \text{elimTB } \varphi \psi \implies \text{no-imp } \varphi \implies \text{no-imp } \psi$ 
    by (induct  $\varphi \psi$  rule:  $\text{elimTB.induct}$ , auto)
  }
  thus  $\text{no-imp } \psi$ 
    using  $\text{full-propo-rew-step-inv-stay-conn[of elimTB no-imp-symb } \varphi \psi]$   $\text{assms}$ 
     $\text{no-imp-symb-conn-characterization unfolding no-imp-def by metis}$ 
qed

```

lemma $\text{elimTB-full-propo-rew-step}$:

```

fixes  $\varphi \psi :: 'v \text{ propo}$ 
assumes  $\text{no-equiv } \varphi$  and  $\text{no-imp } \varphi$  and  $\text{full (propo-rew-step elimTB) } \varphi \psi$ 
shows  $\text{no-T-F-except-top-level } \psi$ 
using  $\text{full-propo-rew-step-subformula no-T-F-except-top-level-rew assms elimTB-inv by fastforce}$ 

```

8.4 PushNeg

Push the negation inside the formula, until the litteral.

inductive pushNeg **where**

```

PushNeg1[simp]:  $\text{pushNeg (FNot (FAnd } \varphi \psi)) (FOr (FNot \varphi) (FNot \psi)) \mid$ 
PushNeg2[simp]:  $\text{pushNeg (FNot (FOr } \varphi \psi)) (FAnd (FNot \varphi) (FNot \psi)) \mid$ 
PushNeg3[simp]:  $\text{pushNeg (FNot (FNot } \varphi)) \varphi$ 

```

lemma $\text{pushNeg-transformation-consistent}$:

```

 $A \models \text{FNot (FAnd } \varphi \psi) \longleftrightarrow A \models (\text{FOr (FNot } \varphi) (\text{FNot } \psi))$ 
 $A \models \text{FNot (FOr } \varphi \psi) \longleftrightarrow A \models (\text{FAnd (FNot } \varphi) (\text{FNot } \psi))$ 
 $A \models \text{FNot (FNot } \varphi) \longleftrightarrow A \models \varphi$ 
by auto

```

lemma pushNeg-explicit : $\text{pushNeg } \varphi \psi \implies \forall A. A \models \varphi \longleftrightarrow A \models \psi$
 by (induct $\varphi \psi$ rule: pushNeg.induct , auto)

lemma $\text{pushNeg-consistent}$: $\text{preserves-un-sat pushNeg}$
 unfolding $\text{preserves-un-sat-def}$ by (simp add: pushNeg-explicit)

lemma $\text{pushNeg-lifted-consistant}$:

```

preserves-un-sat (full (propo-rew-step pushNeg))
  by (simp add:  $\text{pushNeg-consistent}$ )

```

fun simple **where**

```

simple  $\text{FT} = \text{True} \mid$ 
simple  $\text{FF} = \text{True} \mid$ 
simple  $(\text{FVar } -) = \text{True} \mid$ 

```

simple - = *False*

lemma *simple-decomp*:

simple $\varphi \longleftrightarrow (\varphi = FT \vee \varphi = FF \vee (\exists x. \varphi = FVar\ x))$
by (*case-tac* φ , *auto*)

lemma *subformula-conn-decomp-simple*:

fixes $\varphi\ \psi :: 'v\ propo$

assumes *s*: *simple* ψ

shows $\varphi \preceq FNot\ \psi \longleftrightarrow (\varphi = FNot\ \psi \vee \varphi = \psi)$

proof -

have $\varphi \preceq conn\ CNot\ [\psi] \longleftrightarrow (\varphi = conn\ CNot\ [\psi] \vee (\exists \psi \in set\ [\psi]. \varphi \preceq \psi))$

using *subformula-conn-decomp wf-conn-helper-facts(1)* **by** *metis*

thus $\varphi \preceq FNot\ \psi \longleftrightarrow (\varphi = FNot\ \psi \vee \varphi = \psi)$ **using** *s* **by** (*auto simp add: simple-decomp*)

qed

lemma *subformula-conn-decomp-explicit[simp]*:

fixes $\varphi :: 'v\ propo$ **and** $x :: 'v$

shows

$\varphi \preceq FNot\ FT \longleftrightarrow (\varphi = FNot\ FT \vee \varphi = FT)$

$\varphi \preceq FNot\ FF \longleftrightarrow (\varphi = FNot\ FF \vee \varphi = FF)$

$\varphi \preceq FNot\ (FVar\ x) \longleftrightarrow (\varphi = FNot\ (FVar\ x) \vee \varphi = FVar\ x)$

by (*auto simp add: subformula-conn-decomp-simple*)

fun *simple-not-symb* **where**

simple-not-symb (*FNot* φ) = (*simple* φ) |

simple-not-symb - = *True*

definition *simple-not* **where**

simple-not = *all-subformula-st simple-not-symb*

declare *simple-not-def[simp]*

lemma *simple-not-Not[simp]*:

$\neg simple-not\ (FNot\ (FAnd\ \varphi\ \psi))$

$\neg simple-not\ (FNot\ (FOr\ \varphi\ \psi))$

by *auto*

lemma *simple-not-step-exists*:

fixes $\varphi\ \psi :: 'v\ propo$

assumes *no-equiv* φ **and** *no-imp* φ

shows $\psi \preceq \varphi \implies \neg simple-not-symb\ \psi \implies \exists \psi'. pushNeg\ \psi\ \psi'$

apply (*induct* ψ , *auto*)

apply (*case-tac* ψ , *auto intro: pushNeg.intros*)

by (*metis assms(1,2) no-imp-Imp(1) no-equiv-eq(1) no-imp-def no-equiv-def*
subformula-in-subformula-not subformula-all-subformula-st)**+**

lemma *simple-not-rew*:

fixes $\varphi :: 'v\ propo$

assumes *noTB*: $\neg simple-not\ \varphi$ **and** *no-equiv*: *no-equiv* φ **and** *no-imp*: *no-imp* φ

shows $\exists \psi\ \psi'. \psi \preceq \varphi \wedge pushNeg\ \psi\ \psi'$

proof -

have $\forall x. simple-not-symb\ (FF :: 'v\ propo) \wedge simple-not-symb\ FT \wedge simple-not-symb\ (FVar\ (x :: 'v))$

by *auto*

moreover {

```

    fix c:: 'v connective and l :: 'v propo list and  $\psi :: 'v propo$ 
    have H: pushNeg (conn c l)  $\psi \implies \neg \text{simple-not-symb (conn c l)}$ 
      by (case-tac (conn c l) rule: pushNeg.cases, simp-all)
  }
  moreover {
    fix x :: 'v
    have H': simple-not FT simple-not FF simple-not (FVar x)
      by simp-all
  }
  moreover {
    fix  $\psi :: 'v propo$ 
    have  $\psi \preceq \varphi \implies \neg \text{simple-not-symb } \psi \implies \exists \psi'. \text{pushNeg } \psi \psi'$ 
      using simple-not-step-exists no-equiv no-imp by blast
  }
  ultimately show ?thesis using no-test-symb-step-exists noTB unfolding simple-not-def by blast
qed

lemma no-T-F-except-top-level-pushNeg1:
  no-T-F-except-top-level (FNot (FAnd  $\varphi \psi$ ))  $\implies$  no-T-F-except-top-level (FOr (FNot  $\varphi$ ) (FNot  $\psi$ ))
  using no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb no-T-F-comp-not no-T-F-decomp(1)
    no-T-F-decomp(2) no-T-F-no-T-F-except-top-level by (metis no-T-F-comp-expanded-explicit(2)
      propo.distinct(5,17))

lemma no-T-F-except-top-level-pushNeg2:
  no-T-F-except-top-level (FNot (FOr  $\varphi \psi$ ))  $\implies$  no-T-F-except-top-level (FAnd (FNot  $\varphi$ ) (FNot  $\psi$ ))
  by auto

lemma no-T-F-symb-pushNeg:
  no-T-F-symb (FOr (FNot  $\varphi'$ ) (FNot  $\psi'$ ))
  no-T-F-symb (FAnd (FNot  $\varphi'$ ) (FNot  $\psi'$ ))
  no-T-F-symb (FNot (FNot  $\varphi'$ ))
  by auto

lemma propo-rew-step-pushNeg-no-T-F-symb:
  propo-rew-step pushNeg  $\varphi \psi \implies$  no-T-F-except-top-level  $\varphi \implies$  no-T-F-symb  $\varphi \implies$  no-T-F-symb  $\psi$ 
  apply (induct rule: propo-rew-step.induct)
  apply (cases rule: pushNeg.cases)
  apply simp-all
  apply (metis no-T-F-symb-pushNeg(1))
  apply (metis no-T-F-symb-pushNeg(2))
  apply (simp, metis all-subformula-st-test-symb-true-phi no-T-F-def)
proof -
  fix  $\varphi \varphi':: 'a propo$  and  $c:: 'a connective$  and  $\xi \xi':: 'a propo list$ 
  assume rel: propo-rew-step pushNeg  $\varphi \varphi'$ 
  and IH: no-T-F  $\varphi \implies$  no-T-F-symb  $\varphi \implies$  no-T-F-symb  $\varphi'$ 
  and wf: wf-conn c ( $\xi @ \varphi \# \xi'$ )
  and n: conn c ( $\xi @ \varphi \# \xi'$ ) = FF  $\vee$  conn c ( $\xi @ \varphi \# \xi'$ ) = FT  $\vee$  no-T-F (conn c ( $\xi @ \varphi \# \xi'$ ))
  and x:  $c \neq CF \wedge c \neq CT \wedge \varphi \neq FF \wedge \varphi \neq FT \wedge (\forall \psi \in \text{set } \xi \cup \text{set } \xi'. \psi \neq FF \wedge \psi \neq FT)$ 
  hence  $c \neq CF \wedge c \neq CT \wedge \text{wf-conn c } (\xi @ \varphi' \# \xi')$ 
    using wf-conn-no-arity-change-helper wf-conn-no-arity-change by metis
  moreover have  $n': \text{no-T-F (conn c } (\xi @ \varphi \# \xi'))$  using n by (simp add: wf wf-conn-list(1,2))
  moreover
  {
    have no-T-F  $\varphi$ 
    by (metis Un-iff all-subformula-st-decomp list.set-intros(1) n' wf no-T-F-def set-append)
  }

```

```

moreover hence no-T-F-symb  $\varphi$ 
  by (simp add: all-subformula-st-test-symb-true-phi no-T-F-def)
ultimately have  $\varphi' \neq FF \wedge \varphi' \neq FT$ 
  using IH no-T-F-symb-false(1) no-T-F-symb-false(2) by blast
hence  $\forall \psi \in \text{set } (\xi @ \varphi' \# \xi'). \psi \neq FF \wedge \psi \neq FT$  using x by auto
}
ultimately show no-T-F-symb (conn c (\xi @ \varphi' \# \xi')) by (simp add: x)
qed

lemma propo-rew-step-pushNeg-no-T-F:
  propo-rew-step pushNeg \varphi \psi \implies no-T-F \varphi \implies no-T-F \psi
proof (induct rule: propo-rew-step.induct)
  case global-rel
  thus ?case
    by (metis (no-types, lifting) no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb
      no-T-F-def no-T-F-except-top-level-pushNeg1 no-T-F-except-top-level-pushNeg2
      no-T-F-no-T-F-except-top-level all-subformula-st-decomp-explicit(3) pushNeg.simps
      simple.simps(1,2,5,6))
  next
    case (propo-rew-one-step-lift \varphi \varphi' c \xi \xi')
    note rel = this(1) and IH = this(2) and wf = this(3) and no-T-F = this(4)
    moreover have wf': wf-conn c (\xi @ \varphi' \# \xi')
      using wf-conn-no-arity-change wf-conn-no-arity-change-helper wf by metis
    ultimately show no-T-F (conn c (\xi @ \varphi' \# \xi')) unfolding no-T-F-def
      apply (simp add: all-subformula-st-decomp wf wf')
      using all-subformula-st-test-symb-true-phi no-T-F-symb-false(1) no-T-F-symb-false(2) by blast
    qed

```

```

lemma pushNeg-inv:
  fixes  $\varphi \psi :: 'v \text{ propo}$ 
  assumes full (propo-rew-step pushNeg) \varphi \psi
  and no-equiv \varphi and no-imp \varphi and no-T-F-except-top-level \varphi
  shows no-equiv \psi and no-imp \psi and no-T-F-except-top-level \psi
proof -
  {
    fix  $\varphi \psi :: 'v \text{ propo}$ 
    assume rel: propo-rew-step pushNeg \varphi \psi
    and no: no-T-F-except-top-level \varphi
    hence no-T-F-except-top-level \psi
    proof -
      {
        assume  $\varphi = FT \vee \varphi = FF$ 
        from rel this have False
        apply (induct rule: propo-rew-step.induct)
        using pushNeg.cases apply blast
        using wf-conn-list(1) wf-conn-list(2) by auto
        hence no-T-F-except-top-level \psi by blast
      }
    moreover {
      assume  $\varphi \neq FT \wedge \varphi \neq FF$ 
      hence no-T-F \varphi by (metis no no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb)
      hence no-T-F \psi using propo-rew-step-pushNeg-no-T-F rel by auto
      hence no-T-F-except-top-level \psi by (simp add: no-T-F-no-T-F-except-top-level)
    }
  }

```



```

    ultimately show no-T-F-except-top-level  $\psi$  by metis
  qed
}
moreover {
  fix  $c :: 'v$  connective and  $\xi \xi' :: 'v$  propo list and  $\zeta \zeta' :: 'v$  propo
  assume rel: propo-rew-step pushNeg  $\zeta \zeta'$ 
  and incl:  $\zeta \preceq \varphi$ 
  and corr: wf-conn  $c (\xi @ \zeta \# \xi')$ 
  and no-T-F: no-T-F-symb-except-toplevel (conn  $c (\xi @ \zeta \# \xi')$ )
  and  $n$ : no-T-F-symb-except-toplevel  $\zeta'$ 
  have no-T-F-symb-except-toplevel (conn  $c (\xi @ \zeta' \# \xi')$ )
  proof
    have  $p$ : no-T-F-symb (conn  $c (\xi @ \zeta \# \xi')$ )
      using corr wf-conn-list(1) wf-conn-list(2) no-T-F-symb-except-toplevel-no-T-F-symb no-T-F
      by blast
    have  $l$ :  $\forall \varphi \in \text{set } (\xi @ \zeta \# \xi'). \varphi \neq FT \wedge \varphi \neq FF$ 
      using corr wf-conn-no-T-F-symb-iff  $p$  by blast
    from rel incl have  $\zeta' \neq FT \wedge \zeta' \neq FF$ 
    apply (induction  $\zeta \zeta'$  rule: propo-rew-step.induct)
    apply (cases rule: pushNeg.cases, auto)
    by (metis assms(4) no-T-F-symb-except-top-level-false-not no-T-F-except-top-level-def
      all-subformula-st-test-symb-true-phi subformula-in-subformula-not
      subformula-all-subformula-st append-is-Nil-conv list.distinct(1)
      wf-conn-no-arity-change-helper wf-conn-list(1,2) wf-conn-no-arity-change)+
    hence  $\forall \varphi \in \text{set } (\xi @ \zeta' \# \xi'). \varphi \neq FT \wedge \varphi \neq FF$  using  $l$  by auto
    moreover have  $c \neq CT \wedge c \neq CF$  using corr by auto
    ultimately show no-T-F-symb (conn  $c (\xi @ \zeta' \# \xi')$ )
      by (metis corr no-T-F-symb-comp wf-conn-no-arity-change wf-conn-no-arity-change-helper)
  qed
}
ultimately show no-T-F-except-top-level  $\psi$ 
using full-propo-rew-step-inv-stay-with-inc[of pushNeg no-T-F-symb-except-toplevel  $\varphi$ ] assms
subformula-refl unfolding no-T-F-except-top-level-def full-unfold by metis
next
{
  fix  $\varphi \psi :: 'v$  propo
  have  $H$ : pushNeg  $\varphi \psi \implies \text{no-equiv } \varphi \implies \text{no-equiv } \psi$ 
    by (induct  $\varphi \psi$  rule: pushNeg.induct, auto)
}
thus no-equiv  $\psi$ 
using full-propo-rew-step-inv-stay-conn[of pushNeg no-equiv-symb  $\varphi \psi$ ]
no-equiv-symb-conn-characterization assms unfolding no-equiv-def full-unfold by metis
next
{
  fix  $\varphi \psi :: 'v$  propo
  have  $H$ : pushNeg  $\varphi \psi \implies \text{no-imp } \varphi \implies \text{no-imp } \psi$ 
    by (induct  $\varphi \psi$  rule: pushNeg.induct, auto)
}
thus no-imp  $\psi$ 
using full-propo-rew-step-inv-stay-conn[of pushNeg no-imp-symb  $\varphi \psi$ ] assms
no-imp-symb-conn-characterization unfolding no-imp-def full-unfold by metis
qed

```

lemma *pushNeg-full-propo-rew-step*:

fixes $\varphi \psi :: 'v \text{ propo}$
assumes
 $\text{no-equiv } \varphi$ **and**
 $\text{no-imp } \varphi$ **and**
 $\text{full } (\text{propo-rew-step } \text{pushNeg}) \varphi \psi$ **and**
 $\text{no-T-F-except-top-level } \varphi$
shows $\text{simple-not } \psi$
using $\text{assms full-propo-rew-step-subformula pushNeg-inv}(1,2) \text{ simple-not-rew by blast}$

8.5 Push inside

inductive $\text{push-conn-inside} :: 'v \text{ connective} \Rightarrow 'v \text{ connective} \Rightarrow 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$

for $c \ c' :: 'v \text{ connective}$ **where**

$\text{push-conn-inside-l[simp]}: c = CAnd \vee c = COr \Longrightarrow c' = CAnd \vee c' = COr$

$\Longrightarrow \text{push-conn-inside } c \ c' (\text{conn } c [\text{conn } c' [\varphi 1, \varphi 2], \psi])$
 $(\text{conn } c' [\text{conn } c [\varphi 1, \psi], \text{conn } c [\varphi 2, \psi]]) \mid$

$\text{push-conn-inside-r[simp]}: c = CAnd \vee c = COr \Longrightarrow c' = CAnd \vee c' = COr$

$\Longrightarrow \text{push-conn-inside } c \ c' (\text{conn } c [\psi, \text{conn } c' [\varphi 1, \varphi 2]])$
 $(\text{conn } c' [\text{conn } c [\psi, \varphi 1], \text{conn } c [\psi, \varphi 2]])$

lemma $\text{push-conn-inside-explicit}: \text{push-conn-inside } c \ c' \varphi \psi \Longrightarrow \forall A. A \models \varphi \longleftrightarrow A \models \psi$
by ($\text{induct } \varphi \psi \text{ rule: push-conn-inside.induct, auto}$)

lemma $\text{push-conn-inside-consistent}: \text{preserves-un-sat } (\text{push-conn-inside } c \ c')$
unfolding $\text{preserves-un-sat-def}$ **by** ($\text{simp add: push-conn-inside-explicit}$)

lemma $\text{propo-rew-step-push-conn-inside[simp]}:$

$\neg \text{propo-rew-step } (\text{push-conn-inside } c \ c') \text{ FT } \psi \neg \text{propo-rew-step } (\text{push-conn-inside } c \ c') \text{ FF } \psi$

proof –

$\{$
 $\{$
 $\text{fix } \varphi \psi$
 $\text{have } \text{push-conn-inside } c \ c' \varphi \psi \Longrightarrow \varphi = \text{FT} \vee \varphi = \text{FF} \Longrightarrow \text{False}$
 $\text{by } (\text{induct rule: push-conn-inside.induct, auto})$
 $\}$ **note** $H = \text{this}$
 $\text{fix } \varphi$
 $\text{have } \text{propo-rew-step } (\text{push-conn-inside } c \ c') \varphi \psi \Longrightarrow \varphi = \text{FT} \vee \varphi = \text{FF} \Longrightarrow \text{False}$
 $\text{apply } (\text{induct rule: propo-rew-step.induct, auto simp add: wf-conn-list}(1) \text{ wf-conn-list}(2))$
 $\text{using } H \text{ by blast+}$

$\}$

thus

$\neg \text{propo-rew-step } (\text{push-conn-inside } c \ c') \text{ FT } \psi$
 $\neg \text{propo-rew-step } (\text{push-conn-inside } c \ c') \text{ FF } \psi$ **by** blast+

qed

inductive $\text{not-c-in-c'-symb} :: 'v \text{ connective} \Rightarrow 'v \text{ connective} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **for** $c \ c'$ **where**

$\text{not-c-in-c'-symb-l[simp]}: \text{wf-conn } c [\text{conn } c' [\varphi, \varphi'], \psi] \Longrightarrow \text{wf-conn } c' [\varphi, \varphi']$

$\Longrightarrow \text{not-c-in-c'-symb } c \ c' (\text{conn } c [\text{conn } c' [\varphi, \varphi'], \psi]) \mid$

$\text{not-c-in-c'-symb-r[simp]}: \text{wf-conn } c [\psi, \text{conn } c' [\varphi, \varphi']] \Longrightarrow \text{wf-conn } c' [\varphi, \varphi']$

$\Longrightarrow \text{not-c-in-c'-symb } c \ c' (\text{conn } c [\psi, \text{conn } c' [\varphi, \varphi']])$

abbreviation $c\text{-in-c'-symb } c \ c' \varphi \equiv \neg \text{not-c-in-c'-symb } c \ c' \varphi$

lemma *c-in-c'-symb-simp*:

not-c-in-c'-symb c c' $\xi \implies \xi = FF \vee \xi = FT \vee \xi = FVar x \vee \xi = FNot FF \vee \xi = FNot FT$
 $\vee \xi = FNot (FVar x) \implies False$

apply (*induct rule: not-c-in-c'-symb.induct*, *auto simp add: wf-conn.simps wf-conn-list(1-3)*)

using *conn-inj-not(2)* *wf-conn-binary* **unfolding** *binary-connectives-def* **by** *fastforce+*

lemma *c-in-c'-symb-simp'[simp]*:

$\neg not-c-in-c'-symb\ c\ c'\ FF$

$\neg not-c-in-c'-symb\ c\ c'\ FT$

$\neg not-c-in-c'-symb\ c\ c'\ (FVar\ x)$

$\neg not-c-in-c'-symb\ c\ c'\ (FNot\ FF)$

$\neg not-c-in-c'-symb\ c\ c'\ (FNot\ FT)$

$\neg not-c-in-c'-symb\ c\ c'\ (FNot\ (FVar\ x))$

using *c-in-c'-symb-simp* **by** *metis+*

definition *c-in-c'-only* **where**

c-in-c'-only c c' $\equiv all-subformula-st\ (c-in-c'-symb\ c\ c')$

lemma *c-in-c'-only-simp[simp]*:

c-in-c'-only c c' FF

c-in-c'-only c c' FT

c-in-c'-only c c' (FVar x)

c-in-c'-only c c' (FNot FF)

c-in-c'-only c c' (FNot FT)

c-in-c'-only c c' (FNot (FVar x))

unfolding *c-in-c'-only-def* **by** *auto*

lemma *not-c-in-c'-symb-commute*:

not-c-in-c'-symb c c' $\xi \implies wf-conn\ c\ [\varphi, \psi] \implies \xi = conn\ c\ [\varphi, \psi]$

$\implies not-c-in-c'-symb\ c\ c'\ (conn\ c\ [\psi, \varphi])$

proof (*induct rule: not-c-in-c'-symb.induct*)

case (*not-c-in-c'-symb-r $\varphi' \varphi'' \psi'$*) **note** *H = this*

hence $\psi = conn\ c'\ [\varphi'', \psi']$ **using** *conn-inj* **by** *auto*

have *wf-conn c [conn c' [φ'' , ψ'], φ]*

using *H(1)* *wf-conn-no-arity-change length-Cons* **by** *metis*

thus *not-c-in-c'-symb c c' (conn c [ψ , φ])*

unfolding ψ **using** *not-c-in-c'-symb.intros(1)* *H* **by** *auto*

next

case (*not-c-in-c'-symb-l $\varphi' \varphi'' \psi'$*) **note** *H = this*

hence $\varphi = conn\ c'\ [\varphi', \varphi'']$ **using** *conn-inj* **by** *auto*

moreover have *wf-conn c [ψ' , conn c' [φ' , φ'']]*

using *H(1)* *wf-conn-no-arity-change length-Cons* **by** *metis*

ultimately show *not-c-in-c'-symb c c' (conn c [ψ , φ])*

using *not-c-in-c'-symb.intros(2)* *conn-inj not-c-in-c'-symb-l.hyps*

not-c-in-c'-symb-l.prem(1,2) **by** *blast*

qed

lemma *not-c-in-c'-symb-commute'*:

wf-conn c [φ , ψ] $\implies c-in-c'-symb\ c\ c'\ (conn\ c\ [\varphi, \psi]) \longleftrightarrow c-in-c'-symb\ c\ c'\ (conn\ c\ [\psi, \varphi])$

using *not-c-in-c'-symb-commute wf-conn-no-arity-change* **by** (*metis length-Cons*)

lemma *not-c-in-c'-comm*:

assumes *wf: wf-conn c [φ , ψ]*

shows *c-in-c'-only c c' (conn c [φ , ψ]) $\longleftrightarrow c-in-c'-only\ c\ c'\ (conn\ c\ [\psi, \varphi])$ (is ?A \longleftrightarrow ?B)*

proof –

have $?A \longleftrightarrow (c\text{-in-}c'\text{-symb } c \ c' \ (conn \ c \ [\varphi, \psi])$
 $\wedge (\forall \xi \in set \ [\varphi, \psi]. \ all\text{-subformula-st } (c\text{-in-}c'\text{-symb } c \ c') \ \xi))$
using *all-subformula-st-decomp wf unfolding c-in-c'-only-def by fastforce*
also have $\dots \longleftrightarrow (c\text{-in-}c'\text{-symb } c \ c' \ (conn \ c \ [\psi, \varphi])$
 $\wedge (\forall \xi \in set \ [\psi, \varphi]. \ all\text{-subformula-st } (c\text{-in-}c'\text{-symb } c \ c') \ \xi))$
using *not-c-in-c'-symb-commute' wf by auto*
also
have *wf-conn c [\psi, \varphi] using wf-conn-no-arity-change wf by (metis length-Cons)*
hence $(c\text{-in-}c'\text{-symb } c \ c' \ (conn \ c \ [\psi, \varphi])$
 $\wedge (\forall \xi \in set \ [\psi, \varphi]. \ all\text{-subformula-st } (c\text{-in-}c'\text{-symb } c \ c') \ \xi))$
 $\longleftrightarrow ?B$
using *all-subformula-st-decomp unfolding c-in-c'-only-def by fastforce*
finally show *?thesis .*

qed

lemma *not-c-in-c'-simp[simp]:*

fixes $\varphi1 \ \varphi2 \ \psi :: 'v \ propo$ **and** $x :: 'v$
shows
 $c\text{-in-}c'\text{-symb } c \ c' \ FT$
 $c\text{-in-}c'\text{-symb } c \ c' \ FF$
 $c\text{-in-}c'\text{-symb } c \ c' \ (FVar \ x)$
 $wf\text{-conn } c \ [conn \ c' \ [\varphi1, \varphi2], \psi] \implies wf\text{-conn } c' \ [\varphi1, \varphi2]$
 $\implies \neg c\text{-in-}c'\text{-only } c \ c' \ (conn \ c \ [conn \ c' \ [\varphi1, \varphi2], \psi])$
apply (*simp-all add: c-in-c'-only-def*)
using *all-subformula-st-test-symb-true-phi not-c-in-c'-symb-l by blast*

lemma *c-in-c'-symb-not[simp]:*

fixes $c \ c' :: 'v \ connective$ **and** $\psi :: 'v \ propo$
shows $c\text{-in-}c'\text{-symb } c \ c' \ (FNot \ \psi)$

proof –

{
fix $\xi :: 'v \ propo$
have $not\text{-}c\text{-in-}c'\text{-symb } c \ c' \ (FNot \ \psi) \implies False$
apply (*induct FNot \psi rule: not-c-in-c'-symb.induct*)
using *conn-inj-not(2) by blast+*
}

thus *?thesis by auto*

qed

lemma *c-in-c'-symb-step-exists:*

fixes $\varphi :: 'v \ propo$
assumes $c: c = CAnd \vee c = COr$ **and** $c': c' = CAnd \vee c' = COr$
shows $\psi \preceq \varphi \implies \neg c\text{-in-}c'\text{-symb } c \ c' \ \psi \implies \exists \psi'. \ push\text{-conn-inside } c \ c' \ \psi \ \psi'$
apply (*induct \psi rule: propo-induct-arity*)
apply *auto[2]*

proof –

fix $\psi1 \ \psi2 \ \varphi': 'v \ propo$
assume $IH\psi1: \psi1 \preceq \varphi \implies \neg c\text{-in-}c'\text{-symb } c \ c' \ \psi1 \implies Ex \ (push\text{-conn-inside } c \ c' \ \psi1)$
and $IH\psi2: \psi2 \preceq \varphi \implies \neg c\text{-in-}c'\text{-symb } c \ c' \ \psi2 \implies Ex \ (push\text{-conn-inside } c \ c' \ \psi2)$
and $\varphi': \varphi' = FAnd \ \psi1 \ \psi2 \vee \varphi' = FOr \ \psi1 \ \psi2 \vee \varphi' = FImp \ \psi1 \ \psi2 \vee \varphi' = FEq \ \psi1 \ \psi2$
and $in\varphi: \varphi' \preceq \varphi$ **and** $n0: \neg c\text{-in-}c'\text{-symb } c \ c' \ \varphi'$
hence $n: not\text{-}c\text{-in-}c'\text{-symb } c \ c' \ \varphi'$ **by** *auto*
{
assume $\varphi': \varphi' = conn \ c \ [\psi1, \psi2]$

```

obtain  $a\ b$  where  $\psi1 = \text{conn } c' [a, b] \vee \psi2 = \text{conn } c' [a, b]$ 
  using  $n\ \varphi'$  apply (induct rule: not-c-in-c'-symb.induct)
  using  $c$  by force+
hence  $Ex\ (\text{push-conn-inside } c\ c'\ \varphi')$ 
  unfolding  $\varphi'$  apply auto
  using  $\text{push-conn-inside.intros}(1)\ c\ c'$  apply blast
  using  $\text{push-conn-inside.intros}(2)\ c\ c'$  by blast
}
moreover {
  assume  $\varphi': \varphi' \neq \text{conn } c\ [\psi1, \psi2]$ 
  have  $\forall \varphi\ c\ ca. \exists \varphi1\ \psi1\ \psi2\ \psi1'\ \psi2'\ \varphi2'. \text{conn } (c::'v\ \text{connective})\ [\varphi1, \text{conn } ca\ [\psi1, \psi2]] = \varphi$ 
     $\vee \text{conn } c\ [\text{conn } ca\ [\psi1', \psi2'], \varphi2'] = \varphi \vee c\text{-in-}c'\text{-symb } c\ ca\ \varphi$ 
  by (metis not-c-in-c'-symb.cases)
  hence  $Ex\ (\text{push-conn-inside } c\ c'\ \varphi')$ 
  by (metis (no-types) c\ c'\ n\ push-conn-inside-l\ push-conn-inside-r)
}
ultimately show  $Ex\ (\text{push-conn-inside } c\ c'\ \varphi')$  by blast
qed

```

lemma *c-in-c'-symb-rew:*

```

fixes  $\varphi :: 'v\ \text{propo}$ 
assumes  $\text{noTB}: \neg c\text{-in-}c'\text{-only } c\ c'\ \varphi$ 
and  $c: c = CAnd \vee c = COr$  and  $c': c' = CAnd \vee c' = COr$ 
shows  $\exists \psi\ \psi'. \psi \preceq \varphi \wedge \text{push-conn-inside } c\ c'\ \psi\ \psi'$ 
proof –
  have test-symb-false-nullary:
     $\forall x. c\text{-in-}c'\text{-symb } c\ c'\ (FF:: 'v\ \text{propo}) \wedge c\text{-in-}c'\text{-symb } c\ c'\ FT$ 
     $\wedge c\text{-in-}c'\text{-symb } c\ c'\ (FVar\ (x:: 'v))$ 
  by auto
  moreover {
    fix  $x :: 'v$ 
    have  $H': c\text{-in-}c'\text{-symb } c\ c'\ FT\ c\text{-in-}c'\text{-symb } c\ c'\ FF\ c\text{-in-}c'\text{-symb } c\ c'\ (FVar\ x)$ 
    by simp+
  }
  moreover {
    fix  $\psi :: 'v\ \text{propo}$ 
    have  $\psi \preceq \varphi \implies \neg c\text{-in-}c'\text{-symb } c\ c'\ \psi \implies \exists \psi'. \text{push-conn-inside } c\ c'\ \psi\ \psi'$ 
    by (auto simp add: assms(2) c'\ c-in-c'-symb-step-exists)
  }
  ultimately show ?thesis using  $\text{noTB}\ \text{no-test-symb-step-exists[of } c\text{-in-}c'\text{-symb } c\ c']$ 
  unfolding c-in-c'-only-def by metis
qed

```

lemma *push-conn-insidec-in-c'-symb-no-T-F:*

```

fixes  $\varphi\ \psi :: 'v\ \text{propo}$ 
shows  $\text{propo-rew-step } (\text{push-conn-inside } c\ c')\ \varphi\ \psi \implies \text{no-T-F } \varphi \implies \text{no-T-F } \psi$ 
proof (induct rule: propo-rew-step.induct)
  case (global-rel  $\varphi\ \psi$ )
  thus  $\text{no-T-F } \psi$ 
  by (cases rule: push-conn-inside.cases, auto)
next
  case (propo-rew-one-step-lift  $\varphi\ \varphi'\ c\ \xi\ \xi'$ )
  note  $\text{rel} = \text{this}(1)$  and  $\text{IH} = \text{this}(2)$  and  $\text{wf} = \text{this}(3)$  and  $\text{no-T-F} = \text{this}(4)$ 
  have  $\text{no-T-F } \varphi$ 

```

```

using wf no-T-F no-T-F-def subformula-into-subformula subformula-all-subformula-st
subformula-refl by (metis (no-types) in-set-conv-decomp)
hence  $\varphi'$ : no-T-F  $\varphi'$  using IH by blast

have  $\forall \zeta \in \text{set } (\xi @ \varphi \# \xi')$ . no-T-F  $\zeta$  by (metis wf no-T-F no-T-F-def all-subformula-st-decomp)
hence  $n$ :  $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi')$ . no-T-F  $\zeta$  using  $\varphi'$  by auto
hence  $n'$ :  $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi')$ .  $\zeta \neq FF \wedge \zeta \neq FT$ 
using  $\varphi'$  by (metis no-T-F-symb-false(1) no-T-F-symb-false(2) no-T-F-def
all-subformula-st-test-symb-true-phi)

have wf': wf-conn c ( $\xi @ \varphi' \# \xi'$ )
using wf wf-conn-no-arity-change by (metis wf-conn-no-arity-change-helper)
{
  fix x :: 'v
  assume c = CT  $\vee$  c = CF  $\vee$  c = CVar x
  hence False using wf by auto
  hence no-T-F (conn c ( $\xi @ \varphi' \# \xi'$ )) by blast
}
moreover {
  assume c: c = CNot
  hence  $\xi = [] \ \xi' = []$  using wf by auto
  hence no-T-F (conn c ( $\xi @ \varphi' \# \xi'$ ))
    using c by (metis  $\varphi'$  conn.simps(4) no-T-F-symb-false(1,2) no-T-F-symb-fnot no-T-F-def
all-subformula-st-decomp-explicit(3) all-subformula-st-test-symb-true-phi self-append-conv2)
}
moreover {
  assume c: c  $\in$  binary-connectives
  hence no-T-F-symb (conn c ( $\xi @ \varphi' \# \xi'$ )) using wf' n' no-T-F-symb.simps by fastforce
  hence no-T-F (conn c ( $\xi @ \varphi' \# \xi'$ )) by (metis all-subformula-st-decomp-imp wf' n no-T-F-def)
}
ultimately show no-T-F (conn c ( $\xi @ \varphi' \# \xi'$ )) using connective-cases-arity by auto
qed

```

```

lemma simple-propo-rew-step-push-conn-inside-inv:
propo-rew-step (push-conn-inside c c')  $\varphi \ \psi \implies$  simple  $\varphi \implies$  simple  $\psi$ 
apply (induct rule: propo-rew-step.induct)
apply (case-tac  $\varphi$ , auto simp add: push-conn-inside.simps)[1]
by (metis append-is-Nil-conv list.distinct(1) simple.elims(2) wf-conn-list(1-3))

```

```

lemma simple-propo-rew-step-inv-push-conn-inside-simple-not:
fixes c c' :: 'v connective and  $\varphi \ \psi$  :: 'v propo
shows propo-rew-step (push-conn-inside c c')  $\varphi \ \psi \implies$  simple-not  $\varphi \implies$  simple-not  $\psi$ 
proof (induct rule: propo-rew-step.induct)
case (global-rel  $\varphi \ \psi$ )
thus ?case by (case-tac  $\varphi$ , auto simp add: push-conn-inside.simps)
next
case (propo-rew-one-step-lift  $\varphi \ \varphi'$  ca  $\xi \ \xi'$ )
thus ?case
proof (case-tac ca rule: connective-cases-arity, auto)
fix  $\varphi \ \varphi'$  :: 'v propo and c :: 'v connective and  $\xi \ \xi'$  :: 'v propo list
assume rel: propo-rew-step (push-conn-inside c c')  $\varphi \ \varphi'$ 
assume simple  $\varphi$ 
thus simple  $\varphi'$  using rel simple-propo-rew-step-push-conn-inside-inv by blast

```

```

next
  fix  $\varphi \varphi'$  :: 'v propo and  $ca$  :: 'v connective and  $\xi \xi'$  :: 'v propo list
  assume rel: propo-rew-step (push-conn-inside  $c \ c'$ )  $\varphi \varphi'$ 
  and IH: all-subformula-st simple-not-symb  $\varphi \implies$  all-subformula-st simple-not-symb  $\varphi'$ 
  and wf: wf-conn  $ca (\xi @ \varphi \# \xi')$ 
  and simple-not: all-subformula-st simple-not-symb (conn  $ca (\xi @ \varphi \# \xi')$ )
  and  $ca$ :  $ca \in$  binary-connectives

  obtain  $a \ b$  where  $ab$ :  $\xi @ \varphi' \# \xi' = [a, b]$ 
  using wf  $ca$  list-length2-decomp wf-conn-bin-list-length
  by (metis (no-types) wf-conn-no-arity-change-helper)
  have  $\forall \zeta \in$  set  $(\xi @ \varphi \# \xi')$ . simple-not  $\zeta$ 
  by (metis wf all-subformula-st-decomp simple-not simple-not-def)
  hence  $\forall \zeta \in$  set  $(\xi @ \varphi' \# \xi')$ . simple-not  $\zeta$  by (simp add: IH)
  moreover have simple-not-symb (conn  $ca (\xi @ \varphi' \# \xi')$ ) using  $ca$ 
  by (metis  $ab$  conn.simps(5-8) helper-fact simple-not-symb.simps(5) simple-not-symb.simps(6)
    simple-not-symb.simps(7) simple-not-symb.simps(8))
  ultimately show all-subformula-st simple-not-symb (conn  $ca (\xi @ \varphi' \# \xi')$ )
  by (simp add:  $ab$  all-subformula-st-decomp  $ca$ )
qed
qed

```

lemma propo-rew-step-push-conn-inside-simple-not:

```

fixes  $\varphi \varphi'$  :: 'v propo and  $\xi \xi'$  :: 'v propo list and  $c$  :: 'v connective
shows propo-rew-step (push-conn-inside  $c \ c'$ )  $\varphi \varphi' \implies$  wf-conn  $c (\xi @ \varphi \# \xi')$ 
 $\implies$  simple-not-symb (conn  $c (\xi @ \varphi \# \xi')$ )  $\implies$  simple-not-symb  $\varphi'$ 
 $\implies$  simple-not-symb (conn  $c (\xi @ \varphi' \# \xi')$ )
apply (induct rule: propo-rew-step.induct)
apply (metis (no-types, lifting) append-eq-append-conv2 append-self-conv conn.simps(4)
  conn-inj-not(1) global-rel simple-not-symb.elims(3) simple-not-symb.simps(1)
  simple-propo-rew-step-push-conn-inside-inv wf-conn-list-decomp(4) wf-conn-no-arity-change
  wf-conn-no-arity-change-helper)

```

proof (case-tac c rule: connective-cases-arity, auto)

```

fix  $\varphi \varphi'$  :: 'v propo and  $ca$  :: 'v connective and  $\chi s \ \chi s'$  :: 'v propo list
assume simple-not-symb (conn  $c (\xi @$  conn  $ca (\chi s @ \varphi \# \chi s') \# \xi')$ )
and simple-not-symb (conn  $ca (\chi s @ \varphi' \# \chi s')$ )
and corr: wf-conn  $c (\xi @$  conn  $ca (\chi s @ \varphi \# \chi s') \# \xi')$ 
and  $c$ :  $c \in$  binary-connectives
have corr': wf-conn  $c (\xi @$  conn  $ca (\chi s @ \varphi' \# \chi s') \# \xi')$ 
  using corr wf-conn-no-arity-change by (metis wf-conn-no-arity-change-helper)
obtain  $a \ b$  where  $\xi @$  conn  $ca (\chi s @ \varphi' \# \chi s') \# \xi' = [a, b]$ 
  using corr'  $c$  list-length2-decomp wf-conn-bin-list-length by metis
thus simple-not-symb (conn  $c (\xi @$  conn  $ca (\chi s @ \varphi' \# \chi s') \# \xi')$ )
  using  $c$  unfolding binary-connectives-def by auto

```

next

```

fix  $\varphi \varphi'$  :: 'v propo and  $ca$  :: 'v connective and  $\chi s \ \chi s'$  :: 'v propo list
assume corr-ca: wf-conn  $ca (\chi s @ \varphi \# \chi s')$ 
and simple-not: simple (conn  $ca (\chi s @ \varphi \# \chi s')$ )
hence False
proof (case-tac  $ca$  rule: connective-cases-arity)
  fix  $x$  :: 'v
  assume simple (conn  $ca (\chi s @ \varphi \# \chi s')$ ) and  $ca = CT \vee ca = CF \vee ca = CVar \ x$ 
  hence  $\chi s @ \varphi \# \chi s' = []$  using corr-ca by auto
  thus False by auto

```

```

next
  assume simple: simple (conn ca ( $\chi s @ \varphi \# \chi s'$ ))
  and ca: ca  $\in$  binary-connectives
  obtain a b where ab:  $\chi s @ \varphi \# \chi s' = [a, b]$ 
    using corr-ca ca list-length2-decomp wf-conn-bin-list-length
    by (metis append-assoc length-Cons length-append length-append-singleton)
  thus False using simple ca ab conn.simps(5,6,7,8) unfolding binary-connectives-def by auto
next
  assume simple: simple (conn ca ( $\chi s @ \varphi \# \chi s'$ ))
  and ca: ca = CNot
  hence empty:  $\chi s = [] \chi s' = []$  using corr-ca by auto
  thus False using simple ca conn.simps(4) by auto
qed
thus simple (conn ca ( $\chi s @ \varphi' \# \chi s'$ )) by blast
qed

```

lemma *push-conn-inside-not-true-false*:
 $\text{push-conn-inside } c \ c' \ \varphi \ \psi \implies \psi \neq FT \wedge \psi \neq FF$
 by (induct rule: push-conn-inside.induct, auto)

lemma *push-conn-inside-inv*:
 fixes $\varphi \ \psi :: 'v \text{ propo}$
 assumes full (propo-rew-step (push-conn-inside c c') $\varphi \ \psi$)
 and no-equiv φ and no-imp φ and no-T-F-except-top-level φ and simple-not φ
 shows no-equiv ψ and no-imp ψ and no-T-F-except-top-level ψ and simple-not ψ

proof –

```

{
  {
    fix  $\varphi \ \psi :: 'v \text{ propo}$ 
    have H: push-conn-inside c c'  $\varphi \ \psi \implies \text{all-subformula-st simple-not-symb } \varphi$ 
       $\implies \text{all-subformula-st simple-not-symb } \psi$ 
      by (induct  $\varphi \ \psi$  rule: push-conn-inside.induct, auto)
  } note H = this
}

```

```

fix  $\varphi \ \psi :: 'v \text{ propo}$ 
have H: propo-rew-step (push-conn-inside c c')  $\varphi \ \psi \implies \text{all-subformula-st simple-not-symb } \varphi$ 
   $\implies \text{all-subformula-st simple-not-symb } \psi$ 
  apply (induct  $\varphi \ \psi$  rule: propo-rew-step.induct)
  using H apply simp
proof (case-tac ca rule: connective-cases-arity)
  fix  $\varphi \ \varphi' :: 'v \text{ propo}$  and c:: 'v connective and  $\xi \ \xi' :: 'v \text{ propo list}$ 
  and x:: 'v
  assume wf-conn c ( $\xi @ \varphi \# \xi'$ )
  and c = CT  $\vee$  c = CF  $\vee$  c = CVar x
  hence  $\xi @ \varphi \# \xi' = []$  by auto
  hence False by auto
  thus all-subformula-st simple-not-symb (conn c ( $\xi @ \varphi' \# \xi'$ )) by blast
next
  fix  $\varphi \ \varphi' :: 'v \text{ propo}$  and ca:: 'v connective and  $\xi \ \xi' :: 'v \text{ propo list}$ 
  and x :: 'v
  assume rel: propo-rew-step (push-conn-inside c c')  $\varphi \ \varphi'$ 
  and  $\varphi\text{-}\varphi'$ : all-subformula-st simple-not-symb  $\varphi \implies \text{all-subformula-st simple-not-symb } \varphi'$ 
  and corr: wf-conn ca ( $\xi @ \varphi \# \xi'$ )
  and n: all-subformula-st simple-not-symb (conn ca ( $\xi @ \varphi \# \xi'$ ))
  and c: ca = CNot

```



```

have empty:  $\xi = [] \ \xi' = []$  using c corr by auto
hence simple-not:all-subformula-st simple-not-symb (FNot  $\varphi$ ) using corr c n by auto
hence simple  $\varphi$ 
  using all-subformula-st-test-symb-true-phi simple-not-symb.simps(1) by blast
hence simple  $\varphi'$ 
  using rel simple-propo-rew-step-push-conn-inside-inv by blast
thus all-subformula-st simple-not-symb (conn ca ( $\xi @ \varphi' \# \xi'$ )) using c empty
  by (metis simple-not  $\varphi$ - $\varphi'$  append-Nil conn.simps(4) all-subformula-st-decomp-explicit(3)
      simple-not-symb.simps(1))
next
fix  $\varphi \ \varphi' :: 'v$  propo and ca :: 'v connective and  $\xi \ \xi' :: 'v$  propo list
and x :: 'v
assume rel: propo-rew-step (push-conn-inside c c')  $\varphi \ \varphi'$ 
and n $\varphi$ : all-subformula-st simple-not-symb  $\varphi \implies$  all-subformula-st simple-not-symb  $\varphi'$ 
and corr: wf-conn ca ( $\xi @ \varphi \# \xi'$ )
and n: all-subformula-st simple-not-symb (conn ca ( $\xi @ \varphi \# \xi'$ ))
and c: ca  $\in$  binary-connectives

have all-subformula-st simple-not-symb  $\varphi$ 
  using n c corr all-subformula-st-decomp by fastforce
hence  $\varphi'$ : all-subformula-st simple-not-symb  $\varphi'$  using n $\varphi$  by blast
obtain a b where ab:  $[a, b] = (\xi @ \varphi \# \xi')$ 
  using corr c list-length2-decomp wf-conn-bin-list-length by metis
hence  $\xi @ \varphi' \# \xi' = [a, \varphi'] \vee (\xi @ \varphi' \# \xi') = [\varphi', b]$ 
  using ab by (metis (no-types, hide-lams) append-Cons append-Nil append-Nil2
      append-is-Nil-conv butlast.simps(2) butlast-append list.sel(3) tl-append2)
moreover
{
  fix  $\chi :: 'v$  propo
  have wf': wf-conn ca  $[a, b]$ 
    using ab corr by presburger
  have all-subformula-st simple-not-symb (conn ca  $[a, b]$ )
    using ab n by presburger
  hence all-subformula-st simple-not-symb  $\chi \vee \chi \notin$  set ( $\xi @ \varphi' \# \xi'$ )
    using wf' by (metis (no-types)  $\varphi'$  all-subformula-st-decomp calculation insert-iff
        list.set(2))
}
hence  $\forall \varphi. \varphi \in$  set ( $\xi @ \varphi' \# \xi'$ )  $\longrightarrow$  all-subformula-st simple-not-symb  $\varphi$ 
  by (metis (no-types))

moreover have simple-not-symb (conn ca ( $\xi @ \varphi' \# \xi'$ ))
  using ab conn-inj-not(1) corr wf-conn-list-decomp(4) wf-conn-no-arity-change
      not-Cons-self2 self-append-conv2 simple-not-symb.elims(3) by (metis (no-types) c
      calculation(1) wf-conn-binary)
moreover have wf-conn ca ( $\xi @ \varphi' \# \xi'$ ) using c calculation(1) by auto
ultimately show all-subformula-st simple-not-symb (conn ca ( $\xi @ \varphi' \# \xi'$ ))
  by (metis all-subformula-st-decomp-imp)
qed
}
moreover {
  fix ca :: 'v connective and  $\xi \ \xi' :: 'v$  propo list and  $\varphi \ \varphi' :: 'v$  propo
  have propo-rew-step (push-conn-inside c c')  $\varphi \ \varphi' \implies$  wf-conn ca ( $\xi @ \varphi \# \xi'$ )
     $\implies$  simple-not-symb (conn ca ( $\xi @ \varphi \# \xi'$ ))  $\implies$  simple-not-symb  $\varphi'$ 
     $\implies$  simple-not-symb (conn ca ( $\xi @ \varphi' \# \xi'$ ))

```

```

    by (metis append-self-conv2 conn.simps(4) conn-inj-not(1) simple-not-symb.elims(3)
        simple-not-symb.simps(1) simple-propo-rew-step-push-conn-inside-inv
        wf-conn-no-arity-change-helper wf-conn-list-decomp(4) wf-conn-no-arity-change)
  }
  ultimately show simple-not  $\psi$ 
  using full-propo-rew-step-inv-stay'[of push-conn-inside  $c$   $c'$  simple-not-symb] assms
  unfolding no-T-F-except-top-level-def simple-not-def full-unfold by metis
next
{
  fix  $\varphi \psi :: 'v$  propo
  have  $H$ : propo-rew-step (push-conn-inside  $c$   $c'$ )  $\varphi \psi \implies$  no-T-F-except-top-level  $\varphi$ 
     $\implies$  no-T-F-except-top-level  $\psi$ 
  proof -
    assume rel: propo-rew-step (push-conn-inside  $c$   $c'$ )  $\varphi \psi$ 
    and no-T-F-except-top-level  $\varphi$ 
    hence no-T-F  $\varphi \vee \varphi = FF \vee \varphi = FT$ 
      by (metis no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb)
    moreover {
      assume  $\varphi = FF \vee \varphi = FT$ 
      hence False using rel propo-rew-step-push-conn-inside by blast
      hence no-T-F-except-top-level  $\psi$  by blast
    }
    moreover {
      assume no-T-F  $\varphi \wedge \varphi \neq FF \wedge \varphi \neq FT$ 
      hence no-T-F  $\psi$  using rel push-conn-insidec-in-c'-symb-no-T-F by blast
      hence no-T-F-except-top-level  $\psi$  using no-T-F-no-T-F-except-top-level by blast
    }
    ultimately show no-T-F-except-top-level  $\psi$  by blast
  qed
}
moreover {
  fix  $ca :: 'v$  connective and  $\xi \xi' :: 'v$  propo list and  $\varphi \varphi' :: 'v$  propo
  assume rel: propo-rew-step (push-conn-inside  $c$   $c'$ )  $\varphi \varphi'$ 
  assume corr: wf-conn  $ca$  ( $\xi @ \varphi \# \xi'$ )
  hence  $c$ :  $ca \neq CT \wedge ca \neq CF$  by auto
  assume no-T-F: no-T-F-symb-except-toplevel (conn  $ca$  ( $\xi @ \varphi \# \xi'$ ))
  have no-T-F-symb-except-toplevel (conn  $ca$  ( $\xi @ \varphi' \# \xi'$ ))
  proof
    have  $c$ :  $ca \neq CT \wedge ca \neq CF$  using corr by auto
    have  $\zeta$ :  $\forall \zeta \in \text{set } (\xi @ \varphi \# \xi'). \zeta \neq FT \wedge \zeta \neq FF$ 
      using corr no-T-F no-T-F-symb-except-toplevel-if-is-a-true-false by blast
    hence  $\varphi \neq FT \wedge \varphi \neq FF$  by auto
    from rel this have  $\varphi' \neq FT \wedge \varphi' \neq FF$ 
      apply (induct rule: propo-rew-step.induct)
      by (metis append-is-Nil-conv conn.simps(2) conn-inj list.distinct(1)
          wf-conn-helper-facts(3) wf-conn-list(1) wf-conn-no-arity-change
          wf-conn-no-arity-change-helper push-conn-inside-not-true-false)+
    hence  $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi'). \zeta \neq FT \wedge \zeta \neq FF$  using  $\zeta$  by auto
    moreover have wf-conn  $ca$  ( $\xi @ \varphi' \# \xi'$ )
      using corr wf-conn-no-arity-change by (metis wf-conn-no-arity-change-helper)
    ultimately show no-T-F-symb (conn  $ca$  ( $\xi @ \varphi' \# \xi'$ )) using no-T-F-symb.intros  $c$  by metis
  qed
}
ultimately show no-T-F-except-top-level  $\psi$ 
using full-propo-rew-step-inv-stay'[of push-conn-inside  $c$   $c'$  no-T-F-symb-except-toplevel]

```

assms **unfolding** *no-T-F-except-top-level-def full-unfold* **by** *metis*

next

```
{
  fix  $\varphi \psi :: 'v \text{ propo}$ 
  have  $H: \text{push-conn-inside } c \ c' \ \varphi \ \psi \implies \text{no-equiv } \varphi \implies \text{no-equiv } \psi$ 
    by (induct  $\varphi \ \psi$  rule: push-conn-inside.induct, auto)
}
thus no-equiv  $\psi$ 
using full-propo-rew-step-inv-stay-conn[of push-conn-inside  $c \ c'$  no-equiv-symb] assms
no-equiv-symb-conn-characterization unfolding no-equiv-def by metis
```

next

```
{
  fix  $\varphi \psi :: 'v \text{ propo}$ 
  have  $H: \text{push-conn-inside } c \ c' \ \varphi \ \psi \implies \text{no-imp } \varphi \implies \text{no-imp } \psi$ 
    by (induct  $\varphi \ \psi$  rule: push-conn-inside.induct, auto)
}
thus no-imp  $\psi$ 
using full-propo-rew-step-inv-stay-conn[of push-conn-inside  $c \ c'$  no-imp-symb] assms
no-imp-symb-conn-characterization unfolding no-imp-def by metis
```

qed

lemma *push-conn-inside-full-propo-rew-step*:

```
fixes  $\varphi \psi :: 'v \text{ propo}$ 
assumes
  no-equiv  $\varphi$  and
  no-imp  $\varphi$  and
  full (propo-rew-step (push-conn-inside  $c \ c'$ ))  $\varphi \ \psi$  and
  no-T-F-except-top-level  $\varphi$  and
  simple-not  $\varphi$  and
   $c = CAnd \vee c = COr$  and
   $c' = CAnd \vee c' = COr$ 
shows c-in-c'-only  $c \ c' \ \psi$ 
using c-in-c'-symb-rew assms full-propo-rew-step-subformula by blast
```

8.5.1 Only one type of connective in the formula (+ not)

inductive *only-c-inside-symb* :: $'v \text{ connective} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **for** $c :: 'v \text{ connective}$ **where**
simple-only-c-inside[*simp*]: $\text{simple } \varphi \implies \text{only-c-inside-symb } c \ \varphi \mid$
simple-cnot-only-c-inside[*simp*]: $\text{simple } \varphi \implies \text{only-c-inside-symb } c \ (FNot \ \varphi) \mid$
only-c-inside-into-only-c-inside: $\text{wf-conn } c \ l \implies \text{only-c-inside-symb } c \ (\text{conn } c \ l)$

lemma *only-c-inside-symb-simp*[*simp*]:

```
only-c-inside-symb  $c \ FF$  only-c-inside-symb  $c \ FT$  only-c-inside-symb  $c \ (FVar \ x)$  by auto
```

definition *only-c-inside* **where** *only-c-inside* $c = \text{all-subformula-st } (\text{only-c-inside-symb } c)$

lemma *only-c-inside-symb-decomp*:

```
only-c-inside-symb  $c \ \psi \longleftrightarrow (\text{simple } \psi$ 
   $\vee (\exists \ \varphi'. \ \psi = FNot \ \varphi' \wedge \text{simple } \varphi')$ 
   $\vee (\exists \ l. \ \psi = \text{conn } c \ l \wedge \text{wf-conn } c \ l))$ 
by (auto simp add: only-c-inside-symb.intros(3)) (induct rule: only-c-inside-symb.induct, auto)
```

```

lemma only-c-inside-symb-decomp-not[simp]:
  fixes  $c :: 'v$  connective
  assumes  $c: c \neq CNot$ 
  shows only-c-inside-symb  $c$  ( $FNot\ \psi$ )  $\longleftrightarrow$  simple  $\psi$ 
  apply (auto simp add: only-c-inside-symb.intros(3))
  by (induct  $FNot\ \psi$  rule: only-c-inside-symb.induct, auto simp add: wf-conn-list(8)  $c$ )

lemma only-c-inside-decomp-not[simp]:
  assumes  $c: c \neq CNot$ 
  shows only-c-inside  $c$  ( $FNot\ \psi$ )  $\longleftrightarrow$  simple  $\psi$ 
  by (metis (no-types, hide-lams) all-subformula-st-def all-subformula-st-test-symb-true-phi c
    only-c-inside-def only-c-inside-symb-decomp-not simple-only-c-inside
    subformula-conn-decomp-simple)

lemma only-c-inside-decomp:
  only-c-inside  $c\ \varphi \longleftrightarrow$ 
    ( $\forall \psi. \psi \preceq \varphi \longrightarrow$  (simple  $\psi \vee (\exists \varphi'. \psi = FNot\ \varphi' \wedge$  simple  $\varphi')$ 
       $\vee (\exists l. \psi = conn\ c\ l \wedge wf-conn\ c\ l))$ )
  unfolding only-c-inside-def by (auto simp add: all-subformula-st-def only-c-inside-symb-decomp)

lemma only-c-inside-c-c'-false:
  fixes  $c\ c' :: 'v$  connective and  $l :: 'v$  propo list and  $\varphi :: 'v$  propo
  assumes  $cc': c \neq c'$  and  $c: c = CAnd \vee c = COr$  and  $c': c' = CAnd \vee c' = COr$ 
  and only: only-c-inside  $c\ \varphi$  and incl:  $conn\ c'\ l \preceq \varphi$  and wf: wf-conn  $c'\ l$ 
  shows False
proof -
  let  $?\psi = conn\ c'\ l$ 
  have simple  $?\psi \vee (\exists \varphi'. ?\psi = FNot\ \varphi' \wedge$  simple  $\varphi') \vee (\exists l. ?\psi = conn\ c\ l \wedge wf-conn\ c\ l)$ 
    using only-c-inside-decomp only incl by blast
  moreover have  $\neg$  simple  $?\psi$ 
    using wf simple-decomp by (metis  $c'$  connective.distinct(19) connective.distinct(7,9,21,29,31)
      wf-conn-list(1-3))
  moreover
  {
    fix  $\varphi'$ 
    have  $?\psi \neq FNot\ \varphi'$  using  $c'$  conn-inj-not(1) wf by blast
  }
  ultimately obtain  $l :: 'v$  propo list where  $?\psi = conn\ c\ l \wedge wf-conn\ c\ l$  by metis
  hence  $c = c'$  using conn-inj wf by metis
  thus False using  $cc'$  by auto
qed

lemma only-c-inside-implies-c-in-c'-symb:
  assumes  $\delta: c \neq c'$  and  $c: c = CAnd \vee c = COr$  and  $c': c' = CAnd \vee c' = COr$ 
  shows only-c-inside  $c\ \varphi \implies c-in-c'-symb\ c\ c'\ \varphi$ 
  apply (rule ccontr)
  apply (cases rule: not-c-in-c'-symb.cases, auto)
  by (metis  $\delta\ c\ c'$  connective.distinct(37,39) list.distinct(1) only-c-inside-c-c'-false
    subformula-in-binary-conn(1,2) wf-conn.simps)+

lemma c-in-c'-symb-decomp-level1:
  fixes  $l :: 'v$  propo list and  $c\ c' ca :: 'v$  connective
  shows wf-conn  $ca\ l \implies ca \neq c \implies c-in-c'-symb\ c\ c'\ (conn\ ca\ l)$ 

```

proof –

have $\text{not-c-in-c'-symb } c \ c' \ (\text{conn } ca \ l) \implies \text{wf-conn } ca \ l \implies ca = c$
by ($\text{induct conn } ca \ l$ rule: $\text{not-c-in-c'-symb.induct}$, $\text{auto simp add: conn-inj}$)
thus $\text{wf-conn } ca \ l \implies ca \neq c \implies \text{c-in-c'-symb } c \ c' \ (\text{conn } ca \ l)$ **by** *blast*

qed

lemma *only-c-inside-implies-c-in-c'-only*:

assumes δ : $c \neq c'$ **and** c : $c = CAnd \vee c = COr$ **and** c' : $c' = CAnd \vee c' = COr$
shows $\text{only-c-inside } c \ \varphi \implies \text{c-in-c'-only } c \ c' \ \varphi$
unfolding c-in-c'-only-def $\text{all-subformula-st-def}$
using $\text{only-c-inside-implies-c-in-c'-symb}$
by ($\text{metis all-subformula-st-def assms(1) } c \ c' \ \text{only-c-inside-def subformula-trans}$)

lemma *c-in-c'-symb-c-implies-only-c-inside*:

assumes δ : $c = CAnd \vee c = COr$ $c' = CAnd \vee c' = COr$ $c \neq c'$ **and** wf : $\text{wf-conn } c \ [\varphi, \psi]$
and inv : $\text{no-equiv } (\text{conn } c \ l) \ \text{no-imp } (\text{conn } c \ l) \ \text{simple-not } (\text{conn } c \ l)$
shows $\text{wf-conn } c \ l \implies \text{c-in-c'-only } c \ c' \ (\text{conn } c \ l) \implies (\forall \psi \in \text{set } l. \ \text{only-c-inside } c \ \psi)$

using inv

proof ($\text{induct conn } c \ l$ arbitrary: l rule: $\text{propo-induct-arity}$)

case ($\text{nullary } x$)

thus $?case$ **by** ($\text{auto simp add: wf-conn-list assms}$)

next

case ($\text{unary } \varphi \ la$)

hence $c = CNot \wedge la = [\varphi]$ **by** ($\text{metis (no-types) wf-conn-list(8)}$)

thus $?case$ **using** assms(2) assms(1) **by** *blast*

next

case ($\text{binary } \varphi1 \ \varphi2$)

note $IH\varphi1 = \text{this(1)}$ **and** $IH\varphi2 = \text{this(2)}$ **and** $\varphi = \text{this(3)}$ **and** $\text{only} = \text{this(5)}$ **and** $\text{wf} = \text{this(4)}$

and $\text{no-equiv} = \text{this(6)}$ **and** $\text{no-imp} = \text{this(7)}$ **and** $\text{simple-not} = \text{this(8)}$

hence l : $l = [\varphi1, \varphi2]$ **by** ($\text{meson wf-conn-list(4-7)}$)

let $? \varphi = \text{conn } c \ l$

obtain $c1 \ l1 \ c2 \ l2$ **where** $\varphi1$: $\varphi1 = \text{conn } c1 \ l1$ **and** $\text{wf}\varphi1$: $\text{wf-conn } c1 \ l1$

and $\varphi2$: $\varphi2 = \text{conn } c2 \ l2$ **and** $\text{wf}\varphi2$: $\text{wf-conn } c2 \ l2$ **using** exists-c-conn **by** metis

hence $\text{c-in-only}\varphi1$: $\text{c-in-c'-only } c \ c' \ (\text{conn } c1 \ l1)$ **and** $\text{c-in-c'-only } c \ c' \ (\text{conn } c2 \ l2)$

using $\text{only } l$ **unfolding** c-in-c'-only-def **using** assms(1) **by** auto

have $\text{inc}\varphi1$: $\varphi1 \preceq ? \varphi$ **and** $\text{inc}\varphi2$: $\varphi2 \preceq ? \varphi$

using $\varphi1 \ \varphi2 \ \varphi \ \text{local.wf}$ **by** ($\text{metis conn.simps(5-8) helper-fact subformula-in-binary-conn(1,2)}$) $+$

have $c1\text{-eq}$: $c1 \neq CEq$ **and** $c2\text{-eq}$: $c2 \neq CEq$

unfolding no-equiv-def **using** $\text{inc}\varphi1 \ \text{inc}\varphi2$ **by** ($\text{metis } \varphi1 \ \varphi2 \ \text{wf}\varphi1 \ \text{wf}\varphi2 \ \text{assms(1) no-equiv no-equiv-eq(1) no-equiv-symb.elims(3) no-equiv-symb-conn-characterization wf-conn-list(4,5) no-equiv-def subformula-all-subformula-st}$) $+$

have $c1\text{-imp}$: $c1 \neq CImp$ **and** $c2\text{-imp}$: $c2 \neq CImp$

using no-imp **by** ($\text{metis } \varphi1 \ \varphi2 \ \text{all-subformula-st-decomp-explicit-imp(2,3) assms(1) conn.simps(5,6) } l \ \text{no-imp-Imp(1) no-imp-symb.elims(3) no-imp-symb-conn-characterization wf}\varphi1 \ \text{wf}\varphi2 \ \text{all-subformula-st-decomp no-imp-symb-conn-characterization}$) $+$

have $c1c$: $c1 \neq c'$

proof

assume $c1c$: $c1 = c'$

then obtain $\xi1 \ \xi2$ **where** $l1$: $l1 = [\xi1, \xi2]$

by ($\text{metis assms(2) connective.distinct(37,39) helper-fact wf}\varphi1 \ \text{wf-conn.simps wf-conn-list-decomp(1-3)}$)

```

have c-in-c'-only c c' (conn c [conn c' l1,  $\varphi 2$ ]) using c1c l only  $\varphi 1$  by auto
moreover have not-c-in-c'-symb c c' (conn c [conn c' l1,  $\varphi 2$ ])
  using l1  $\varphi 1$  c1c l local.wf not-c-in-c'-symb-l wf $\varphi 1$  by blast
ultimately show False using  $\varphi 1$  c1c l l1 local.wf not-c-in-c'-simp(4) wf $\varphi 1$  by blast
qed
hence ( $\varphi 1 = \text{conn } c \text{ l1} \wedge \text{wf-conn } c \text{ l1}$ )  $\vee$  ( $\exists \psi 1. \varphi 1 = \text{FNot } \psi 1$ )  $\vee$  simple  $\varphi 1$ 
  by (metis  $\varphi 1$  assms(1-3) c1-eq c1-imp simple.elims(3) wf $\varphi 1$  wf-conn-list(4) wf-conn-list(5-7))
moreover {
  assume  $\varphi 1 = \text{conn } c \text{ l1} \wedge \text{wf-conn } c \text{ l1}$ 
  hence only-c-inside c  $\varphi 1$ 
  by (metis IH $\varphi 1$   $\varphi 1$  all-subformula-st-decomp-imp inc $\varphi 1$  no-equiv no-equiv-def no-imp no-imp-def
    c-in-only $\varphi 1$  only-c-inside-def only-c-inside-into-only-c-inside simple-not simple-not-def
    subformula-all-subformula-st)
}
moreover {
  assume  $\exists \psi 1. \varphi 1 = \text{FNot } \psi 1$ 
  then obtain  $\psi 1$  where  $\varphi 1 = \text{FNot } \psi 1$  by metis
  hence only-c-inside c  $\varphi 1$ 
  by (metis all-subformula-st-def assms(1) connective.distinct(37,39) inc $\varphi 1$ 
    only-c-inside-decomp-not simple-not simple-not-def simple-not-symb.simps(1))
}
moreover {
  assume simple  $\varphi 1$ 
  hence only-c-inside c  $\varphi 1$ 
  by (metis all-subformula-st-decomp-explicit(3) assms(1) connective.distinct(37,39)
    only-c-inside-decomp-not only-c-inside-def)
}
ultimately have only-c-inside $\varphi 1$ : only-c-inside c  $\varphi 1$  by metis

have c-in-only $\varphi 2$ : c-in-c'-only c c' (conn c2 l2)
  using only l  $\varphi 2$  wf $\varphi 2$  assms unfolding c-in-c'-only-def by auto
have c2c: c2  $\neq$  c'
proof
  assume c2c: c2 = c'
  then obtain  $\xi 1 \xi 2$  where l2: l2 = [ $\xi 1, \xi 2$ ]
  by (metis assms(2) wf $\varphi 2$  wf-conn.simps connective.distinct(7,9,19,21,29,31,37,39))
  hence c-in-c'-symb c c' (conn c [ $\varphi 1$ , conn c' l2])
  using c2c l only  $\varphi 2$  all-subformula-st-test-symb-true-phi unfolding c-in-c'-only-def by auto
  moreover have not-c-in-c'-symb c c' (conn c [ $\varphi 1$ , conn c' l2])
  using assms(1) c2c l2 not-c-in-c'-symb-r wf $\varphi 2$  wf-conn-helper-facts(5,6) by metis
  ultimately show False by auto
qed
hence ( $\varphi 2 = \text{conn } c \text{ l2} \wedge \text{wf-conn } c \text{ l2}$ )  $\vee$  ( $\exists \psi 2. \varphi 2 = \text{FNot } \psi 2$ )  $\vee$  simple  $\varphi 2$ 
  using c2-eq by (metis  $\varphi 2$  assms(1-3) c2-eq c2-imp simple.elims(3) wf $\varphi 2$  wf-conn-list(4-7))
moreover {
  assume  $\varphi 2 = \text{conn } c \text{ l2} \wedge \text{wf-conn } c \text{ l2}$ 
  hence only-c-inside c  $\varphi 2$ 
  by (metis IH $\varphi 2$   $\varphi 2$  all-subformula-st-decomp inc $\varphi 2$  no-equiv no-equiv-def no-imp no-imp-def
    c-in-only $\varphi 2$  only-c-inside-def only-c-inside-into-only-c-inside simple-not simple-not-def
    subformula-all-subformula-st)
}
moreover {
  assume  $\exists \psi 2. \varphi 2 = \text{FNot } \psi 2$ 
  then obtain  $\psi 2$  where  $\varphi 2 = \text{FNot } \psi 2$  by metis
  hence only-c-inside c  $\varphi 2$ 

```

```

    by (metis all-subformula-st-def assms(1-3) connective.distinct(38,40) incφ2
        only-c-inside-decomp-not simple-not simple-not-def simple-not-symb.simps(1))
  }
  moreover {
    assume simple φ2
    hence only-c-inside c φ2
    by (metis all-subformula-st-decomp-explicit(3) assms(1) connective.distinct(37,39)
        only-c-inside-decomp-not only-c-inside-def)
  }
  ultimately have only-c-insideφ2: only-c-inside c φ2 by metis
  show ?case using l only-c-insideφ1 only-c-insideφ2 by auto
qed

```

8.5.2 Push Conjunction

definition *pushConj* **where** *pushConj* = *push-conn-inside CAnd COr*

lemma *pushConj-consistent: preserves-un-sat pushConj*
unfolding *pushConj-def* **by** (*simp add: push-conn-inside-consistent*)

definition *and-in-or-symb* **where** *and-in-or-symb* = *c-in-c'-symb CAnd COr*

definition *and-in-or-only* **where**
and-in-or-only = *all-subformula-st (c-in-c'-symb CAnd COr)*

lemma *pushConj-inv:*
fixes $\varphi \psi :: 'v \text{ propo}$
assumes *full (propo-rew-step pushConj) $\varphi \psi$*
and *no-equiv φ and no-imp φ and no-T-F-except-top-level φ and simple-not φ*
shows *no-equiv ψ and no-imp ψ and no-T-F-except-top-level ψ and simple-not ψ*
using *push-conn-inside-inv assms unfolding pushConj-def by metis+*

lemma *pushConj-full-propo-rew-step:*
fixes $\varphi \psi :: 'v \text{ propo}$
assumes
no-equiv φ and
no-imp φ and
full (propo-rew-step pushConj) $\varphi \psi$ and
no-T-F-except-top-level φ and
simple-not φ
shows *and-in-or-only ψ*
using *assms push-conn-inside-full-propo-rew-step*
unfolding *pushConj-def and-in-or-only-def c-in-c'-only-def by (metis (no-types))*

8.5.3 Push Disjunction

definition *pushDisj* **where** *pushDisj* = *push-conn-inside COr CAnd*

lemma *pushDisj-consistent: preserves-un-sat pushDisj*
unfolding *pushDisj-def* **by** (*simp add: push-conn-inside-consistent*)

definition *or-in-and-symb* **where** *or-in-and-symb* = *c-in-c'-symb COr CAnd*

definition *or-in-and-only* **where**
or-in-and-only = *all-subformula-st (c-in-c'-symb COr CAnd)*

lemma *not-or-in-and-only-or-and*[simp]:
 $\sim \text{or-in-and-only } (FOr \ (FAnd \ \psi1 \ \psi2) \ \varphi')$
unfolding *or-in-and-only-def*
by (*metis all-subformula-st-test-symb-true-phi conn.simps(5-6) not-c-in-c'-symb-l*
wf-conn-helper-facts(5) wf-conn-helper-facts(6))

lemma *pushDisj-inv*:
fixes $\varphi \ \psi :: 'v \text{ propo}$
assumes *full (propo-rew-step pushDisj) $\varphi \ \psi$*
and *no-equiv φ and no-imp φ and no-T-F-except-top-level φ and simple-not φ*
shows *no-equiv ψ and no-imp ψ and no-T-F-except-top-level ψ and simple-not ψ*
using *push-conn-inside-inv assms unfolding pushDisj-def by metis+*

lemma *pushDisj-full-propo-rew-step*:
fixes $\varphi \ \psi :: 'v \text{ propo}$
assumes
no-equiv φ and
no-imp φ and
full (propo-rew-step pushDisj) $\varphi \ \psi$ and
no-T-F-except-top-level φ and
simple-not φ
shows *or-in-and-only ψ*
using *assms push-conn-inside-full-propo-rew-step*
unfolding *pushDisj-def or-in-and-only-def c-in-c'-only-def by (metis (no-types))*

9 The full transformations

9.1 Abstract Property characterizing that only some connective are inside the others

9.1.1 Definition

The normal is a super group of groups

inductive *grouped-by* :: *'a connective \Rightarrow 'a propo \Rightarrow bool for c where*
simple-is-grouped[simp]: *simple $\varphi \Rightarrow$ grouped-by c φ |*
simple-not-is-grouped[simp]: *simple $\varphi \Rightarrow$ grouped-by c (FNot φ) |*
connected-is-group[simp]: *grouped-by c $\varphi \Rightarrow$ grouped-by c $\psi \Rightarrow$ wf-conn c $[\varphi, \psi]$*
 \Rightarrow *grouped-by c (conn c $[\varphi, \psi]$)*

lemma *simple-clause*[simp]:
grouped-by c FT
grouped-by c FF
grouped-by c (FVar x)
grouped-by c (FNot FT)
grouped-by c (FNot FF)
grouped-by c (FNot (FVar x))
by *simp+*

lemma *only-c-inside-symb-c-eq-c'*:
only-c-inside-symb c (conn c' $[\varphi1, \varphi2]$) \Rightarrow $c' = CAnd \vee c' = COr \Rightarrow$ wf-conn c' $[\varphi1, \varphi2]$
 \Rightarrow *$c' = c$*
by (*induct conn c' $[\varphi1, \varphi2]$ rule: only-c-inside-symb.induct, auto simp add: conn-inj*)

lemma *only-c-inside-c-eq-c'*:

only-c-inside c (*conn* c' [$\varphi 1$, $\varphi 2$]) $\implies c' = CAnd \vee c' = COr \implies wf\text{-}conn\ c' [\varphi 1, \varphi 2] \implies c = c'$
unfolding *only-c-inside-def* *all-subformula-st-def* **using** *only-c-inside-symb-c-eq-c'* *subformula-refl*
by *blast*

lemma *only-c-inside-imp-grouped-by*:

assumes $c \neq CNot$ **and** $c': c' = CAnd \vee c' = COr$
shows *only-c-inside* c $\varphi \implies$ *grouped-by* c φ (**is** $?O \varphi \implies ?G \varphi$)

proof (*induct* φ *rule: propo-induct-arity*)

case (*nullary* φ x)

thus $?G \varphi$ **by** *auto*

next

case (*unary* ψ)

thus $?G (FNot \psi)$ **by** (*auto simp add: c*)

next

case (*binary* φ $\varphi 1$ $\varphi 2$)

note $IH\varphi 1 = this(1)$ **and** $IH\varphi 2 = this(2)$ **and** $\varphi = this(3)$ **and** $only = this(4)$

have $\varphi\text{-}conn: \varphi = conn\ c [\varphi 1, \varphi 2]$ **and** $wf: wf\text{-}conn\ c [\varphi 1, \varphi 2]$

proof –

obtain $c''\ l''$ **where** $\varphi\text{-}c'': \varphi = conn\ c''\ l''$ **and** $wf: wf\text{-}conn\ c''\ l''$

using *exists-c-conn* **by** *metis*

hence $l'': l'' = [\varphi 1, \varphi 2]$ **using** φ **by** (*metis wf-conn-list(4-7)*)

have *only-c-inside-symb* c (*conn* $c'' [\varphi 1, \varphi 2]$)

using *only all-subformula-st-test-symb-true-phi*

unfolding *only-c-inside-def* $\varphi\text{-}c''\ l''$ **by** *metis*

hence $c = c''$

by (*metis* $\varphi\ \varphi\text{-}c''\ conn\text{-}inj\ conn\text{-}inj\text{-}not(2)\ l''\ list.distinct(1)\ list.inject\ wf$

only-c-inside-symb.cases simple.simps(5-8))

thus $\varphi = conn\ c [\varphi 1, \varphi 2]$ **and** $wf\text{-}conn\ c [\varphi 1, \varphi 2]$ **using** $\varphi\text{-}c''\ wf\ l''$ **by** *auto*

qed

have *grouped-by* c $\varphi 1$ **using** $wf\ IH\varphi 1\ IH\varphi 2\ \varphi\text{-}conn\ only\ \varphi$ **unfolding** *only-c-inside-def* **by** *auto*

moreover **have** *grouped-by* c $\varphi 2$

using $wf\ \varphi\ IH\varphi 1\ IH\varphi 2\ \varphi\text{-}conn\ only$ **unfolding** *only-c-inside-def* **by** *auto*

ultimately show $?G \varphi$ **using** $\varphi\text{-}conn\ connected\text{-}is\text{-}group\ local.wf$ **by** *blast*

qed

lemma *grouped-by-false*:

grouped-by c (*conn* c' [φ , ψ]) $\implies c \neq c' \implies wf\text{-}conn\ c' [\varphi, \psi] \implies False$

apply (*induct* *conn* c' [φ , ψ] *rule: grouped-by.induct*)

apply (*auto simp add: simple-decomp wf-conn-list, auto simp add: conn-inj*)

by (*metis list.distinct(1) list.sel(3) wf-conn-list(8)*)**+**

Then the CNF form is a conjunction of clauses: every clause is in CNF form and two formulas in CNF form can be related by an and.

inductive *super-grouped-by*:: '*a* *connective* \implies '*a* *connective* \implies '*a* *propo* \implies *bool* **for** $c\ c'$ **where**

grouped-is-super-grouped[*simp*]: *grouped-by* $c\ \varphi \implies$ *super-grouped-by* $c\ c'\ \varphi$ |

connected-is-super-group: *super-grouped-by* $c\ c'\ \varphi \implies$ *super-grouped-by* $c\ c'\ \psi \implies wf\text{-}conn\ c [\varphi, \psi]$

\implies *super-grouped-by* $c\ c' (conn\ c' [\varphi, \psi])$

lemma *simple-cnf*[*simp*]:

super-grouped-by $c\ c'\ FT$

super-grouped-by $c\ c'\ FF$

```

super-grouped-by c c' (FVar x)
super-grouped-by c c' (FNot FT)
super-grouped-by c c' (FNot FF)
super-grouped-by c c' (FNot (FVar x))
by auto

lemma c-in-c'-only-super-grouped-by:
  assumes c: c = CAnd ∨ c = COr and c': c' = CAnd ∨ c' = COr and cc': c ≠ c'
  shows no-equiv φ ⇒ no-imp φ ⇒ simple-not φ ⇒ c-in-c'-only c c' φ
    ⇒ super-grouped-by c c' φ
    (is ?NE φ ⇒ ?NI φ ⇒ ?SN φ ⇒ ?C φ ⇒ ?S φ)
proof (induct φ rule: propo-induct-arity)
  case (nullary φ x)
  thus ?S φ by auto
next
  case (unary φ)
  hence simple-not-symb (FNot φ)
    using all-subformula-st-test-symb-true-phi unfolding simple-not-def by blast
  hence φ = FT ∨ φ = FF ∨ (∃ x. φ = FVar x) by (case-tac φ, auto)
  thus ?S (FNot φ) by auto
next
  case (binary φ φ1 φ2)
  note IHφ1 = this(1) and IHφ2 = this(2) and no-equiv = this(4) and no-imp = this(5)
    and simpleN = this(6) and c-in-c'-only = this(7) and φ' = this(3)
  {
    assume φ = FImp φ1 φ2 ∨ φ = FEq φ1 φ2
    hence False using no-equiv no-imp by auto
    hence ?S φ by auto
  }
  moreover {
    assume φ: φ = conn c' [φ1, φ2] ∧ wf-conn c' [φ1, φ2]
    have c-in-c'-only: c-in-c'-only c c' φ1 ∧ c-in-c'-only c c' φ2 ∧ c-in-c'-symb c c' φ
      using c-in-c'-only φ' unfolding c-in-c'-only-def by auto
    have super-grouped-by c c' φ1 using φ c' no-equiv no-imp simpleN IHφ1 c-in-c'-only by auto
    moreover have super-grouped-by c c' φ2
      using φ c' no-equiv no-imp simpleN IHφ2 c-in-c'-only by auto
    ultimately have ?S φ
      using super-grouped-by.intros(2) φ by (metis c wf-conn-helper-facts(5,6))
  }
  moreover {
    assume φ: φ = conn c [φ1, φ2] ∧ wf-conn c [φ1, φ2]
    hence only-c-inside c φ1 ∧ only-c-inside c φ2
      using c-in-c'-symb-c-implies-only-c-inside c c' c-in-c'-only list.set-intros(1)
        wf-conn-helper-facts(5,6) no-equiv no-imp simpleN last-ConsL last-ConsR last-in-set
        list.distinct(1) by (metis (no-types, hide-lams) cc')
    hence only-c-inside c (conn c [φ1, φ2])
      unfolding only-c-inside-def using φ
      by (simp add: only-c-inside-into-only-c-inside all-subformula-st-decomp)
    hence grouped-by c φ using φ only-c-inside-imp-grouped-by c by blast
    hence ?S φ using super-grouped-by.intros(1) by metis
  }
  ultimately show ?S φ by (metis φ' c c' cc' conn.simps(5,6) wf-conn-helper-facts(5,6))
qed

```

9.2 Conjunctive Normal Form

definition *is-conj-with-TF* **where** *is-conj-with-TF* == *super-grouped-by COr CAnd*

lemma *or-in-and-only-conjunction-in-disj*:

shows *no-equiv* $\varphi \implies$ *no-imp* $\varphi \implies$ *simple-not* $\varphi \implies$ *or-in-and-only* $\varphi \implies$ *is-conj-with-TF* φ

using *c-in-c'-only-super-grouped-by*

unfolding *is-conj-with-TF-def or-in-and-only-def c-in-c'-only-def*

by (*simp add: c-in-c'-only-def c-in-c'-only-super-grouped-by*)

definition *is-cnf* **where** *is-cnf* φ == *is-conj-with-TF* $\varphi \wedge$ *no-T-F-except-top-level* φ

9.2.1 Full CNF transformation

The full CNF transformation consists simply in chaining all the transformation defined before.

definition *cnf-rew* **where** *cnf-rew* =

(*full (propo-rew-step elim-equiv)*) *OO*

(*full (propo-rew-step elim-imp)*) *OO*

(*full (propo-rew-step elimTB)*) *OO*

(*full (propo-rew-step pushNeg)*) *OO*

(*full (propo-rew-step pushDisj)*)

lemma *cnf-rew-consistent: preserves-un-sat cnf-rew*

by (*simp add: cnf-rew-def elimEquiv-lifted-consistant elim-imp-lifted-consistant elimTB-consistent preserves-un-sat-OO pushDisj-consistent pushNeg-lifted-consistant*)

lemma *cnf-rew-is-cnf: cnf-rew* φ $\varphi' \implies$ *is-cnf* φ'

apply (*unfold cnf-rew-def OO-def*)

apply *auto*

proof –

fix φ φEq φImp φTB φNeg \varphiDisj :: '*v propo*

assume *Eq: full (propo-rew-step elim-equiv)* φ φEq

hence *no-equiv: no-equiv* φEq **using** *no-equiv-full-propo-rew-step-elim-equiv* **by** *blast*

assume *Imp: full (propo-rew-step elim-imp)* φEq φImp

hence *no-imp: no-imp* φImp **using** *no-imp-full-propo-rew-step-elim-imp* **by** *blast*

have *no-imp-inv: no-equiv* φImp **using** *no-equiv Imp elim-imp-inv* **by** *blast*

assume *TB: full (propo-rew-step elimTB)* φImp φTB

hence *noTB: no-T-F-except-top-level* φTB

using *no-imp-inv no-imp elimTB-full-propo-rew-step* **by** *blast*

have *noTB-inv: no-equiv* φTB *no-imp* φTB **using** *elimTB-inv TB no-imp no-imp-inv* **by** *blast+*

assume *Neg: full (propo-rew-step pushNeg)* φTB φNeg

hence *noNeg: simple-not* φNeg

using *noTB-inv noTB pushNeg-full-propo-rew-step* **by** *blast*

have *noNeg-inv: no-equiv* φNeg *no-imp* φNeg *no-T-F-except-top-level* φNeg

using *pushNeg-inv Neg noTB noTB-inv* **by** *blast+*

assume *Disj: full (propo-rew-step pushDisj)* φNeg \varphiDisj

hence *no-Disj: or-in-and-only* \varphiDisj

using *noNeg-inv noNeg pushDisj-full-propo-rew-step* **by** *blast*

have *noDisj-inv: no-equiv* \varphiDisj *no-imp* \varphiDisj *no-T-F-except-top-level* \varphiDisj

simple-not \varphiDisj

using *pushDisj-inv Disj noNeg noNeg-inv* by *blast+*
 moreover have *is-conj-with-TF φ Disj*
 using *or-in-and-only-conjunction-in-disj noDisj-inv no-Disj* by *blast*
 ultimately show *is-cnf φ Disj unfolding is-cnf-def* by *blast*
 qed

9.3 Disjunctive Normal Form

definition *is-disj-with-TF* **where** *is-disj-with-TF* \equiv *super-grouped-by CAnd COr*

lemma *and-in-or-only-conjunction-in-disj*:

shows *no-equiv $\varphi \implies$ no-imp $\varphi \implies$ simple-not $\varphi \implies$ and-in-or-only $\varphi \implies$ is-disj-with-TF φ*
 using *c-in-c'-only-super-grouped-by*
 unfolding *is-disj-with-TF-def and-in-or-only-def c-in-c'-only-def*
 by (*simp add: c-in-c'-only-def c-in-c'-only-super-grouped-by*)

definition *is-dnf* $:: 'a \text{ propo} \Rightarrow \text{bool}$ **where**

is-dnf $\varphi \longleftrightarrow$ is-disj-with-TF $\varphi \wedge$ no-T-F-except-top-level φ

9.3.1 Full DNF transform

The full DNF transformation consists simply in chaining all the transformation defined before.

definition *dnf-rew* **where** *dnf-rew* \equiv
 (*full (propo-rew-step elim-equiv)*) *OO*
 (*full (propo-rew-step elim-imp)*) *OO*
 (*full (propo-rew-step elimTB)*) *OO*
 (*full (propo-rew-step pushNeg)*) *OO*
 (*full (propo-rew-step pushConj)*)

lemma *dnf-rew-consistent: preserves-un-sat dnf-rew*

by (*simp add: dnf-rew-def elimEquiv-lifted-consistant elim-imp-lifted-consistant elimTB-consistent preserves-un-sat-OO pushConj-consistent pushNeg-lifted-consistant*)

theorem *dnf-transformation-correction*:

dnf-rew $\varphi \varphi' \implies$ is-dnf φ'
apply (*unfold dnf-rew-def OO-def*)
by (*meson and-in-or-only-conjunction-in-disj elimTB-full-propo-rew-step elimTB-inv(1,2) elim-imp-inv is-dnf-def no-equiv-full-propo-rew-step-elim-equiv no-imp-full-propo-rew-step-elim-imp pushConj-full-propo-rew-step pushConj-inv(1-4) pushNeg-full-propo-rew-step pushNeg-inv(1-3)*)

10 More aggressive simplifications: Removing true and false at the beginning

10.1 Transformation

We should remove *FT* and *FF* at the beginning and not in the middle of the algorithm. To do this, we have to use more rules (one for each connective):

inductive *elimTBFull* **where**

ElimTBFull1[simp]: elimTBFull (FAnd φ FT) φ |
ElimTBFull1'[simp]: elimTBFull (FAnd FT φ) φ |

$ElimTBFull2[simp]: elimTBFull (FAnd \varphi FF) FF \mid$
 $ElimTBFull2'[simp]: elimTBFull (FAnd FF \varphi) FF \mid$

 $ElimTBFull3[simp]: elimTBFull (FOr \varphi FT) FT \mid$
 $ElimTBFull3'[simp]: elimTBFull (FOr FT \varphi) FT \mid$

 $ElimTBFull4[simp]: elimTBFull (FOr \varphi FF) \varphi \mid$
 $ElimTBFull4'[simp]: elimTBFull (FOr FF \varphi) \varphi \mid$

 $ElimTBFull5[simp]: elimTBFull (FNot FT) FF \mid$
 $ElimTBFull5'[simp]: elimTBFull (FNot FF) FT \mid$

 $ElimTBFull6-l[simp]: elimTBFull (FImp FT \varphi) \varphi \mid$
 $ElimTBFull6-l'[simp]: elimTBFull (FImp FF \varphi) FT \mid$
 $ElimTBFull6-r[simp]: elimTBFull (FImp \varphi FT) FT \mid$
 $ElimTBFull6-r'[simp]: elimTBFull (FImp \varphi FF) (FNot \varphi) \mid$

 $ElimTBFull7-l[simp]: elimTBFull (FEq FT \varphi) \varphi \mid$
 $ElimTBFull7-l'[simp]: elimTBFull (FEq FF \varphi) (FNot \varphi) \mid$
 $ElimTBFull7-r[simp]: elimTBFull (FEq \varphi FT) \varphi \mid$
 $ElimTBFull7-r'[simp]: elimTBFull (FEq \varphi FF) (FNot \varphi) \mid$

The transformation is still consistent.

lemma *elimTBFull-consistent: preserves-un-sat elimTBFull*

proof –

```

{
  fix  $\varphi \psi :: 'b \text{ propo}$ 
  have  $elimTBFull \varphi \psi \implies \forall A. A \models \varphi \longleftrightarrow A \models \psi$ 
    by (induct-tac rule: elimTBFull.inducts, auto)
}
thus ?thesis using preserves-un-sat-def by auto
qed

```

Contrary to the theorem $\llbracket no\text{-equiv } ?\varphi; no\text{-imp } ?\varphi; ?\psi \preceq ?\varphi; \neg no\text{-T-F-symb-except-toplevel } ?\psi \rrbracket \implies \exists \psi'. elimTB \ ?\psi \ \psi'$, we do not need the assumption *no-equiv* φ and *no-imp* φ , since our transformation is more general.

lemma *no-T-F-symb-except-toplevel-step-exists'*:

```

fixes  $\varphi :: 'v \text{ propo}$ 
shows  $\psi \preceq \varphi \implies \neg no\text{-T-F-symb-except-toplevel } \psi \implies \exists \psi'. elimTBFull \psi \psi'$ 
proof (induct  $\psi$  rule: propo-induct-arity)
  case (nullary  $\varphi'$ )
  hence False using no-T-F-symb-except-toplevel-true no-T-F-symb-except-toplevel-false by auto
  thus Ex (elimTBFull  $\varphi'$ ) by blast

```

next

```

case (unary  $\psi$ )
  hence  $\psi = FF \vee \psi = FT$  using no-T-F-symb-except-toplevel-not-decom by blast
  thus Ex (elimTBFull (FNot  $\psi$ )) using ElimTBFull5 ElimTBFull5' by blast

```

next

```

case (binary  $\varphi' \psi1 \psi2$ )
  hence  $\psi1 = FT \vee \psi2 = FT \vee \psi1 = FF \vee \psi2 = FF$ 
    by (metis binary-connectives-def conn.simps(5-8) insertI1 insert-commute
      no-T-F-symb-except-toplevel-bin-decom binary.hyps(3))
  thus Ex (elimTBFull  $\varphi'$ ) using elimTBFull.intros binary.hyps(3) by blast

```

qed

The same applies here. We do not need the assumption, but the deep link between $\neg \text{no-T-F-except-top-level}$ φ and the existence of a rewriting step, still exists.

```

lemma no-T-F-except-top-level-rew':
  fixes  $\varphi :: 'v \text{ propo}$ 
  assumes noTB:  $\neg \text{no-T-F-except-top-level } \varphi$ 
  shows  $\exists \psi \psi'. \psi \preceq \varphi \wedge \text{elimTBFull } \psi \psi'$ 
proof –
  have test-symb-false-nullary:
     $\forall x. \text{no-T-F-symb-except-toplevel } (FF :: 'v \text{ propo}) \wedge \text{no-T-F-symb-except-toplevel } FT$ 
     $\wedge \text{no-T-F-symb-except-toplevel } (FVar (x :: 'v))$ 
  by auto
  moreover {
    fix c ::  $'v \text{ connective}$  and l ::  $'v \text{ propo list}$  and  $\psi :: 'v \text{ propo}$ 
    have H:  $\text{elimTBFull } (\text{conn } c \ l) \ \psi \implies \neg \text{no-T-F-symb-except-toplevel } (\text{conn } c \ l)$ 
    by (case-tac ( $\text{conn } c \ l$ ) rule: elimTBFull.cases, simp-all)
  }
  ultimately show ?thesis
  using no-test-symb-step-exists[of no-T-F-symb-except-toplevel  $\varphi$  elimTBFull] noTB
  no-T-F-symb-except-toplevel-step-exists' unfolding no-T-F-except-top-level-def by metis
qed

```

```

lemma elimTBFull-full-propo-rew-step:
  fixes  $\varphi \psi :: 'v \text{ propo}$ 
  assumes full (propo-rew-step elimTBFull)  $\varphi \psi$ 
  shows no-T-F-except-top-level  $\psi$ 
  using full-propo-rew-step-subformula no-T-F-except-top-level-rew' assms by fastforce

```

10.2 More invariants

As the aim is to use the transformation as the first transformation, we have to show some more invariants for *elim-equiv* and *elim-imp*. For the other transformation, we have already proven it.

```

lemma propo-rew-step-ElimEquiv-no-T-F: propo-rew-step elim-equiv  $\varphi \psi \implies \text{no-T-F } \varphi \implies \text{no-T-F } \psi$ 
proof (induct rule: propo-rew-step.induct)
  fix  $\varphi' :: 'v \text{ propo}$  and  $\psi' :: 'v \text{ propo}$ 
  assume a1: no-T-F  $\varphi'$ 
  assume a2: elim-equiv  $\varphi' \psi'$ 
  have  $\forall x0 \ x1. (\neg \text{elim-equiv } (x1 :: 'v \text{ propo}) \ x0 \vee (\exists v2 \ v3 \ v4 \ v5 \ v6 \ v7. x1 = FEq \ v2 \ v3$ 
     $\wedge x0 = FAnd (FImp \ v4 \ v5) (FImp \ v6 \ v7) \wedge v2 = v4 \wedge v4 = v7 \wedge v3 = v5 \wedge v3 = v6))$ 
     $= (\neg \text{elim-equiv } x1 \ x0 \vee (\exists v2 \ v3 \ v4 \ v5 \ v6 \ v7. x1 = FEq \ v2 \ v3$ 
     $\wedge x0 = FAnd (FImp \ v4 \ v5) (FImp \ v6 \ v7) \wedge v2 = v4 \wedge v4 = v7 \wedge v3 = v5 \wedge v3 = v6))$ 
  by meson
  hence  $\forall p \ pa. \neg \text{elim-equiv } (p :: 'v \text{ propo}) \ pa \vee (\exists pb \ pc \ pd \ pe \ pf \ pg. p = FEq \ pb \ pc$ 
     $\wedge pa = FAnd (FImp \ pd \ pe) (FImp \ pf \ pg) \wedge pb = pd \wedge pd = pg \wedge pc = pe \wedge pc = pf)$ 
  using elim-equiv.cases by force
  thus no-T-F  $\psi'$  using a1 a2 by fastforce
next
  fix  $\varphi \varphi' :: 'v \text{ propo}$  and  $\xi \xi' :: 'v \text{ propo list}$  and c ::  $'v \text{ connective}$ 
  assume rel: propo-rew-step elim-equiv  $\varphi \varphi'$ 
  and IH: no-T-F  $\varphi \implies \text{no-T-F } \varphi'$ 
  and corr: wf-conn c ( $\xi @ \varphi \# \xi'$ )
  and no-T-F: no-T-F ( $\text{conn } c \ (\xi @ \varphi \# \xi')$ )

```

```

{
  assume c: c = CNot
  hence empty:  $\xi = [] \ \xi' = []$  using corr by auto
  hence no-T-F  $\varphi$  using no-T-F c no-T-F-decomp-not by auto
  hence no-T-F (conn c ( $\xi @ \varphi' \# \xi'$ )) using c empty no-T-F-comp-not IH by auto
}
moreover {
  assume c: c  $\in$  binary-connectives
  obtain a b where ab:  $\xi @ \varphi \# \xi' = [a, b]$ 
    using corr c list-length2-decomp wf-conn-bin-list-length by metis
  hence  $\varphi$ :  $\varphi = a \vee \varphi = b$ 
    by (metis append.simps(1) append-is-Nil-conv list.distinct(1) list.sel(3) nth-Cons-0
        tl-append2)
  have  $\zeta$ :  $\forall \zeta \in \text{set } (\xi @ \varphi \# \xi'). \text{ no-T-F } \zeta$ 
    using no-T-F unfolding no-T-F-def using corr all-subformula-st-decomp by blast

  hence  $\varphi'$ : no-T-F  $\varphi'$  using ab IH  $\varphi$  by auto
  have  $l'$ :  $\xi @ \varphi' \# \xi' = [\varphi', b] \vee \xi @ \varphi' \# \xi' = [a, \varphi']$ 
    by (metis (no-types, hide-lams) ab append-Cons append-Nil append-Nil2 butlast.simps(2)
        butlast-append list.distinct(1) list.sel(3))
  hence  $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi'). \text{ no-T-F } \zeta$  using  $\zeta \ \varphi' \text{ ab}$  by fastforce
  moreover
    have  $\forall \zeta \in \text{set } (\xi @ \varphi \# \xi'). \zeta \neq FT \wedge \zeta \neq FF$ 
      using  $\zeta$  corr no-T-F no-T-F-except-top-level-false no-T-F-no-T-F-except-top-level by blast
    hence no-T-F-symb (conn c ( $\xi @ \varphi' \# \xi'$ ))
      by (metis  $\varphi' \ l' \text{ ab}$  all-subformula-st-test-symb-true-phi c list.distinct(1)
          list.set-intros(1,2) no-T-F-symb-except-toplevel-bin-decom
          no-T-F-symb-except-toplevel-no-T-F-symb no-T-F-symb-false(1,2) no-T-F-def wf-conn-binary
          wf-conn-list(1,2))
    ultimately have no-T-F (conn c ( $\xi @ \varphi' \# \xi'$ ))
      by (metis  $l' \text{ all-subformula-st-decomp-imp c}$  no-T-F-def wf-conn-binary)
  }
  moreover {
    fix x
    assume c = CVar x  $\vee$  c = CF  $\vee$  c = CT
    hence False using corr by auto
    hence no-T-F (conn c ( $\xi @ \varphi' \# \xi'$ )) by auto
  }
  ultimately show no-T-F (conn c ( $\xi @ \varphi' \# \xi'$ )) using corr wf-conn.cases by metis
}
qed

```

lemma elim-equiv-inv':

fixes $\varphi \ \psi :: 'v \text{ propo}$
 assumes full (propo-rew-step elim-equiv) $\varphi \ \psi$ and no-T-F-except-top-level φ
 shows no-T-F-except-top-level ψ

proof -

```

{
  fix  $\varphi \ \psi :: 'v \text{ propo}$ 
  have propo-rew-step elim-equiv  $\varphi \ \psi \implies \text{no-T-F-except-top-level } \varphi$ 
     $\implies \text{no-T-F-except-top-level } \psi$ 
  proof -
    assume rel: propo-rew-step elim-equiv  $\varphi \ \psi$ 
    and no: no-T-F-except-top-level  $\varphi$ 
    {
      assume  $\varphi = FT \vee \varphi = FF$ 

```

```

    from rel this have False
      apply (induct rule: propo-rew-step.induct, auto simp add: wf-conn-list(1,2))
      using elim-equiv.simps by blast+
    hence no-T-F-except-top-level  $\psi$  by blast
  }
  moreover {
    assume  $\varphi \neq FT \wedge \varphi \neq FF$ 
    hence no-T-F  $\varphi$  by (metis no no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb)
    hence no-T-F  $\psi$  using propo-rew-step-ElimEquiv-no-T-F rel by blast
    hence no-T-F-except-top-level  $\psi$  by (simp add: no-T-F-no-T-F-except-top-level)
  }
  ultimately show no-T-F-except-top-level  $\psi$  by metis
qed
}
moreover {
  fix c :: 'v connective and  $\xi \xi' :: 'v$  propo list and  $\zeta \zeta' :: 'v$  propo
  assume rel: propo-rew-step elim-equiv  $\zeta \zeta'$ 
  and incl:  $\zeta \preceq \varphi$ 
  and corr: wf-conn c ( $\xi @ \zeta \# \xi'$ )
  and no-T-F: no-T-F-symb-except-toplevel (conn c ( $\xi @ \zeta \# \xi'$ ))
  and n: no-T-F-symb-except-toplevel  $\zeta'$ 
  have no-T-F-symb-except-toplevel (conn c ( $\xi @ \zeta' \# \xi'$ ))
  proof
    have p: no-T-F-symb (conn c ( $\xi @ \zeta \# \xi'$ ))
      using corr wf-conn-list(1) wf-conn-list(2) no-T-F-symb-except-toplevel-no-T-F-symb no-T-F
      by blast
    have l:  $\forall \varphi \in \text{set } (\xi @ \zeta \# \xi'). \varphi \neq FT \wedge \varphi \neq FF$ 
      using corr wf-conn-no-T-F-symb-iff p by blast
    from rel incl have  $\zeta' \neq FT \wedge \zeta' \neq FF$ 
      apply (induction  $\zeta \zeta'$  rule: propo-rew-step.induct)
      apply (cases rule: elim-equiv.cases, auto simp add: elim-equiv.simps)
      by (metis append-is-Nil-conv list.distinct wf-conn-list(1,2) wf-conn-no-arity-change
          wf-conn-no-arity-change-helper)+
    hence  $\forall \varphi \in \text{set } (\xi @ \zeta' \# \xi'). \varphi \neq FT \wedge \varphi \neq FF$  using l by auto
    moreover have  $c \neq CT \wedge c \neq CF$  using corr by auto
    ultimately show no-T-F-symb (conn c ( $\xi @ \zeta' \# \xi'$ ))
      by (metis corr wf-conn-no-arity-change wf-conn-no-arity-change-helper no-T-F-symb-comp)
  qed
}
ultimately show no-T-F-except-top-level  $\psi$ 
  using full-propo-rew-step-inv-stay-with-inc[of elim-equiv no-T-F-symb-except-toplevel  $\varphi$ ]
  assms subformula-refl unfolding no-T-F-except-top-level-def by metis
qed

```

```

lemma propo-rew-step-ElimImp-no-T-F: propo-rew-step elim-imp  $\varphi \psi \implies$  no-T-F  $\varphi \implies$  no-T-F  $\psi$ 
proof (induct rule: propo-rew-step.induct)
  case (global-rel  $\varphi' \psi'$ )
  thus no-T-F  $\psi'$ 
    using elim-imp.cases no-T-F-comp-not no-T-F-decomp(1,2)
    by (metis no-T-F-comp-expanded-explicit(2))
next
  case (propo-rew-one-step-lift  $\varphi \varphi' c \xi \xi'$ )
  note rel = this(1) and IH = this(2) and corr = this(3) and no-T-F = this(4)
  {

```



```

assume  $c$ :  $c = CNot$ 
hence  $empty$ :  $\xi = [] \ \xi' = []$  using  $corr$  by  $auto$ 
hence  $no-T-F \ \varphi$  using  $no-T-F \ c \ no-T-F-decomp-not$  by  $auto$ 
hence  $no-T-F \ (conn \ c \ (\xi @ \varphi' \# \xi'))$  using  $c \ empty \ no-T-F-comp-not \ IH$  by  $auto$ 
}
moreover {
  assume  $c$ :  $c \in binary-connectives$ 
  then obtain  $a \ b$  where  $ab$ :  $\xi @ \varphi \# \xi' = [a, b]$ 
    using  $corr \ list-length2-decomp \ wf-conn-bin-list-length$  by  $metis$ 
  hence  $\varphi$ :  $\varphi = a \vee \varphi = b$ 
    by ( $metis \ append-self-conv2 \ wf-conn-list-decomp(4) \ wf-conn-unary \ list.discI \ list.sel(3) \ nth-Cons-0 \ tl-append2$ )
  have  $\zeta$ :  $\forall \zeta \in set \ (\xi @ \varphi \# \xi'). \ no-T-F \ \zeta$  using  $ab \ c \ propo-rew-one-step-lift.prem$ s by  $auto$ 

  hence  $\varphi'$ :  $no-T-F \ \varphi'$ 
    using  $ab \ IH \ \varphi \ corr \ no-T-F \ no-T-F-def \ all-subformula-st-decomp-explicit$  by  $auto$ 
  have  $\chi$ :  $\xi @ \varphi' \# \xi' = [\varphi', b] \vee \xi @ \varphi' \# \xi' = [a, \varphi']$ 
    by ( $metis \ (no-types, \ hide-lams) \ ab \ append-Cons \ append-Nil \ append-Nil2 \ butlast.simps(2) \ butlast-append \ list.distinct(1) \ list.sel(3)$ )
  hence  $\forall \zeta \in set \ (\xi @ \varphi' \# \xi'). \ no-T-F \ \zeta$  using  $\zeta \ \varphi' \ ab$  by  $fastforce$ 
  moreover
    have  $no-T-F \ (last \ (\xi @ \varphi' \# \xi'))$  by ( $simp \ add$ :  $calculation$ )
    hence  $no-T-F-symb \ (conn \ c \ (\xi @ \varphi' \# \xi'))$ 
      by ( $metis \ \chi \ \varphi' \ \zeta \ ab \ all-subformula-st-test-symb-true-phi \ c \ last.simps \ list.distinct(1) \ list.set-intros(1) \ no-T-F-bin-decomp \ no-T-F-def$ )
    ultimately have  $no-T-F \ (conn \ c \ (\xi @ \varphi' \# \xi'))$  using  $c \ \chi$  by  $fastforce$ 
  }
  moreover {
    fix  $x$ 
    assume  $c = CVar \ x \vee c = CF \vee c = CT$ 
    hence  $False$  using  $corr$  by  $auto$ 
    hence  $no-T-F \ (conn \ c \ (\xi @ \varphi' \# \xi'))$  by  $auto$ 
  }
  ultimately show  $no-T-F \ (conn \ c \ (\xi @ \varphi' \# \xi'))$  using  $corr \ wf-conn.cases$  by  $blast$ 
}
qed

```

```

lemma  $elim-imp-inv'$ :
  fixes  $\varphi \ \psi :: 'v \ propo$ 
  assumes  $full \ (propo-rew-step \ elim-imp) \ \varphi \ \psi$  and  $no-T-F-except-top-level \ \varphi$ 
  shows  $no-T-F-except-top-level \ \psi$ 
proof -
{
  {
    fix  $\varphi \ \psi :: 'v \ propo$ 
    have  $H$ :  $elim-imp \ \varphi \ \psi \implies no-T-F-except-top-level \ \varphi \implies no-T-F-except-top-level \ \psi$ 
      by ( $induct \ \varphi \ \psi \ rule: elim-imp.induct, \ auto$ )
    } note  $H = this$ 
    fix  $\varphi \ \psi :: 'v \ propo$ 
    have  $propo-rew-step \ elim-imp \ \varphi \ \psi \implies no-T-F-except-top-level \ \varphi \implies no-T-F-except-top-level \ \psi$ 
    proof -
      assume  $rel$ :  $propo-rew-step \ elim-imp \ \varphi \ \psi$ 
      and  $no$ :  $no-T-F-except-top-level \ \varphi$ 
      {
        assume  $\varphi = FT \vee \varphi = FF$ 

```

```

    from rel this have False
      apply (induct rule: propo-rew-step.induct)
      by (cases rule: elim-imp.cases, auto simp add: wf-conn-list(1,2))
    hence no-T-F-except-top-level  $\psi$  by blast
  }
  moreover {
    assume  $\varphi \neq FT \wedge \varphi \neq FF$ 
    hence no-T-F  $\varphi$  by (metis no no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb)
    hence no-T-F  $\psi$  using rel propo-rew-step-ElimImp-no-T-F by blast
    hence no-T-F-except-top-level  $\psi$  by (simp add: no-T-F-no-T-F-except-top-level)
  }
  ultimately show no-T-F-except-top-level  $\psi$  by metis
qed
}
moreover {
  fix  $c :: 'v$  connective and  $\xi \xi' :: 'v$  propo list and  $\zeta \zeta' :: 'v$  propo
  assume rel: propo-rew-step elim-imp  $\zeta \zeta'$ 
  and incl:  $\zeta \preceq \varphi$ 
  and corr: wf-conn  $c (\xi @ \zeta \# \xi')$ 
  and no-T-F: no-T-F-symb-except-toplevel (conn  $c (\xi @ \zeta \# \xi')$ )
  and n: no-T-F-symb-except-toplevel  $\zeta'$ 
  have no-T-F-symb-except-toplevel (conn  $c (\xi @ \zeta' \# \xi')$ )
  proof
    have  $p$ : no-T-F-symb (conn  $c (\xi @ \zeta \# \xi')$ )
      by (simp add: corr no-T-F no-T-F-symb-except-toplevel-no-T-F-symb wf-conn-list(1,2))

    have  $l$ :  $\forall \varphi \in \text{set } (\xi @ \zeta \# \xi'). \varphi \neq FT \wedge \varphi \neq FF$ 
      using corr wf-conn-no-T-F-symb-iff  $p$  by blast
    from rel incl have  $\zeta' \neq FT \wedge \zeta' \neq FF$ 
      apply (induction  $\zeta \zeta'$  rule: propo-rew-step.induct)
      apply (cases rule: elim-imp.cases, auto)
      using wf-conn-list(1,2) wf-conn-no-arity-change wf-conn-no-arity-change-helper
      by (metis append-is-Nil-conv list.distinct(1))+
    hence  $\forall \varphi \in \text{set } (\xi @ \zeta' \# \xi'). \varphi \neq FT \wedge \varphi \neq FF$  using  $l$  by auto
    moreover have  $c \neq CT \wedge c \neq CF$  using corr by auto
    ultimately show no-T-F-symb (conn  $c (\xi @ \zeta' \# \xi')$ )
      using corr wf-conn-no-arity-change no-T-F-symb-comp
      by (metis wf-conn-no-arity-change-helper)
  qed
}
ultimately show no-T-F-except-top-level  $\psi$ 
  using full-propo-rew-step-inv-stay-with-inc[of elim-imp no-T-F-symb-except-toplevel  $\varphi$ ]
  assms subformula-refl unfolding no-T-F-except-top-level-def by metis
qed

```

10.3 The new CNF and DNF transformation

The transformation is the same as before, but the order is not the same.

definition $dnf\text{-}rew' :: 'a \text{ propo} \Rightarrow 'a \text{ propo} \Rightarrow \text{bool}$ **where** $dnf\text{-}rew' \equiv$
 (full (propo-rew-step elimTBFULL)) OO
 (full (propo-rew-step elim-equiv)) OO
 (full (propo-rew-step elim-imp)) OO
 (full (propo-rew-step pushNeg)) OO
 (full (propo-rew-step pushConj))

lemma *dnf-rew'-consistent: preserves-un-sat dnf-rew'*
by (*simp add: dnf-rew'-def elimEquiv-lifted-consistant elim-imp-lifted-consistant*
elimTBFull-consistent preserves-un-sat-OO pushConj-consistent pushNeg-lifted-consistant)

theorem *cnf-transformation-correction:*

dnf-rew' φ $\varphi' \implies$ is-dnf φ'

unfolding *dnf-rew'-def OO-def*

by (*meson and-in-or-only-conjunction-in-disj elimTBFull-full-propo-rew-step elim-equiv-inv'*
elim-imp-inv elim-imp-inv' is-dnf-def no-equiv-full-propo-rew-step-elim-equiv
no-imp-full-propo-rew-step-elim-imp pushConj-full-propo-rew-step pushConj-inv(1-4)
pushNeg-full-propo-rew-step pushNeg-inv(1-3)))

Given all the lemmas before the CNF transformation is easy to prove:

definition *cnf-rew' :: 'a propo \Rightarrow 'a propo \Rightarrow bool where cnf-rew' \equiv*

(full (propo-rew-step elimTBFull)) OO

(full (propo-rew-step elim-equiv)) OO

(full (propo-rew-step elim-imp)) OO

(full (propo-rew-step pushNeg)) OO

(full (propo-rew-step pushDisj))

lemma *cnf-rew'-consistent: preserves-un-sat cnf-rew'*

by (*simp add: cnf-rew'-def elimEquiv-lifted-consistant elim-imp-lifted-consistant*
elimTBFull-consistent preserves-un-sat-OO pushDisj-consistent pushNeg-lifted-consistant)

theorem *cnf'-transformation-correction:*

cnf-rew' φ $\varphi' \implies$ is-cnf φ'

unfolding *cnf-rew'-def OO-def*

by (*meson elimTBFull-full-propo-rew-step elim-equiv-inv' elim-imp-inv elim-imp-inv' is-cnf-def*
no-equiv-full-propo-rew-step-elim-equiv no-imp-full-propo-rew-step-elim-imp
or-in-and-only-conjunction-in-disj pushDisj-full-propo-rew-step pushDisj-inv(1-4)
pushNeg-full-propo-rew-step pushNeg-inv(1) pushNeg-inv(2) pushNeg-inv(3)))

end

11 Partial Clausal Logic

theory *Partial-Clausal-Logic*

imports *../lib/Clausal-Logic List-More*

begin

11.1 Clauses

Clauses are (finite) multisets of literals.

type-synonym *'a clause = 'a literal multiset*

type-synonym *'v clauses = 'v clause set*

11.2 Partial Interpretations

type-synonym *'a interp = 'a literal set*

definition *true-lit :: 'a interp \Rightarrow 'a literal \Rightarrow bool (infix \models_l 50) where*

$I \models_l L \iff L \in I$

declare *true-lit-def[*simp*]*

11.2.1 Consistency

definition *consistent-interp* :: 'a literal set \Rightarrow bool **where**
consistent-interp $I = (\forall L. \neg(L \in I \wedge \neg L \in I))$

lemma *consistent-interp-empty[simp]*:
consistent-interp $\{\}$ **unfolding** *consistent-interp-def* **by** *auto*

lemma *consistent-interp-single[simp]*:
consistent-interp $\{L\}$ **unfolding** *consistent-interp-def* **by** *auto*

lemma *consistent-interp-subset*:
assumes
 $A \subseteq B$ **and**
consistent-interp B
shows *consistent-interp* A
using *assms* **unfolding** *consistent-interp-def* **by** *auto*

lemma *consistent-interp-change-insert*:
 $a \notin A \Rightarrow \neg a \notin A \Rightarrow \text{consistent-interp } (\text{insert } (-a) A) \longleftrightarrow \text{consistent-interp } (\text{insert } a A)$
unfolding *consistent-interp-def* **by** *fastforce*

lemma *consistent-interp-insert-pos[simp]*:
 $a \notin A \Rightarrow \text{consistent-interp } (\text{insert } a A) \longleftrightarrow \text{consistent-interp } A \wedge \neg a \notin A$
unfolding *consistent-interp-def* **by** *auto*

lemma *consistent-interp-insert-not-in*:
consistent-interp $A \Rightarrow a \notin A \Rightarrow \neg a \notin A \Rightarrow \text{consistent-interp } (\text{insert } a A)$
unfolding *consistent-interp-def* **by** *auto*

11.2.2 Atoms

definition *atms-of-ms* :: 'a literal multiset set \Rightarrow 'a set **where**
atms-of-ms $\psi s = \bigcup (\text{atms-of } ' \psi s)$

lemma *atms-of-msmultiset[simp]*:
atms-of (*mset* a) = *atm-of* ' *set* a
by (*induct* a) *auto*

lemma *atms-of-ms-mset-unfold*:
atms-of-ms (*mset* ' b) = $(\bigcup_{x \in b. \text{atm-of } ' \text{set } x}$
unfolding *atms-of-ms-def* **by** *simp*

definition *atms-of-s* :: 'a literal set \Rightarrow 'a set **where**
atms-of-s $C = \text{atm-of } ' C$

lemma *atms-of-ms-empty-set[simp]*:
atms-of-ms $\{\}$ = $\{\}$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-mempty[simp]*:
atms-of-ms $\{\{\#\}\}$ = $\{\}$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-mono*:
 $A \subseteq B \Rightarrow \text{atms-of-ms } A \subseteq \text{atms-of-ms } B$

unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-finite[simp]*:
finite $\psi s \implies \text{finite } (\text{atms-of-ms } \psi s)$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-union[simp]*:
 $\text{atms-of-ms } (\psi s \cup \chi s) = \text{atms-of-ms } \psi s \cup \text{atms-of-ms } \chi s$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-insert[simp]*:
 $\text{atms-of-ms } (\text{insert } \psi s \chi s) = \text{atms-of } \psi s \cup \text{atms-of-ms } \chi s$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-singleton[simp]*: $\text{atms-of-ms } \{L\} = \text{atms-of } L$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-atms-of-ms-mono[simp]*:
 $A \in \psi \implies \text{atms-of } A \subseteq \text{atms-of-ms } \psi$
unfolding *atms-of-ms-def* **by** *fastforce*

lemma *atms-of-ms-single-set-mset-atms-of[simp]*:
 $\text{atms-of-ms } (\text{single } ' \text{ set-mset } B) = \text{atms-of } B$
unfolding *atms-of-ms-def* *atms-of-def* **by** *auto*

lemma *atms-of-ms-remove-incl*:
shows $\text{atms-of-ms } (\text{Set.remove } a \psi) \subseteq \text{atms-of-ms } \psi$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-remove-subset*:
 $\text{atms-of-ms } (\varphi - \psi) \subseteq \text{atms-of-ms } \varphi$
unfolding *atms-of-ms-def* **by** *auto*

lemma *finite-atms-of-ms-remove-subset[simp]*:
 $\text{finite } (\text{atms-of-ms } A) \implies \text{finite } (\text{atms-of-ms } (A - C))$
using *atms-of-ms-remove-subset[of A C]* *finite-subset* **by** *blast*

lemma *atms-of-ms-empty-iff*:
 $\text{atms-of-ms } A = \{\} \longleftrightarrow A = \{\{\#\}\} \vee A = \{\}$
apply (*rule iffI*)
apply (*metis* (*no-types*, *lifting*) *atms-empty-iff-empty* *atms-of-atms-of-ms-mono* *insert-absorb*
singleton-iff *singleton-insert-inj-eq'* *subsetI* *subset-empty*)
apply *auto*[]
done

lemma *in-implies-atm-of-on-atms-of-ms*:
assumes $L \in \# C$ **and** $C \in N$
shows $\text{atm-of } L \in \text{atms-of-ms } N$
using *atms-of-atms-of-ms-mono[of C N]* *assms* **by** (*simp* *add*: *atm-of-lit-in-atms-of* *subset-iff*)

lemma *in-plus-implies-atm-of-on-atms-of-ms*:
assumes $C + \{\#L\# \} \in N$
shows $\text{atm-of } L \in \text{atms-of-ms } N$
using *in-implies-atm-of-on-atms-of-ms[of C + \{\#L\# \}]* *assms* **by** *auto*

lemma *in-m-in-literals*:
assumes $\{\#A\# \} + D \in \psi_s$
shows $\text{atm-of } A \in \text{atms-of-ms } \psi_s$
using *assms* **by** (*auto dest: atms-of-atms-of-ms-mono*)

lemma *atms-of-s-union[simp]*:
 $\text{atms-of-s } (Ia \cup Ib) = \text{atms-of-s } Ia \cup \text{atms-of-s } Ib$
unfolding *atms-of-s-def* **by** *auto*

lemma *atms-of-s-single[simp]*:
 $\text{atms-of-s } \{L\} = \{\text{atm-of } L\}$
unfolding *atms-of-s-def* **by** *auto*

lemma *atms-of-s-insert[simp]*:
 $\text{atms-of-s } (\text{insert } L \text{ } Ib) = \{\text{atm-of } L\} \cup \text{atms-of-s } Ib$
unfolding *atms-of-s-def* **by** *auto*

lemma *in-atms-of-s-decomp[iff]*:
 $P \in \text{atms-of-s } I \longleftrightarrow (\text{Pos } P \in I \vee \text{Neg } P \in I) \text{ (is } ?P \longleftrightarrow ?Q)$

proof
assume $?P$
then show $?Q$ **unfolding** *atms-of-s-def* **by** (*metis image-iff literal.exhaust-sel*)
next
assume $?Q$
then show $?P$ **unfolding** *atms-of-s-def* **by** *force*
qed

lemma *atm-of-in-atm-of-set-in-uminus*:
 $\text{atm-of } L' \in \text{atm-of } 'B \implies L' \in B \vee - L' \in B$
using *atms-of-s-def* **by** (*cases L' fastforce+*)

11.2.3 Totality

definition *total-over-set* :: $'a \text{ interp} \Rightarrow 'a \text{ set} \Rightarrow \text{bool}$ **where**
 $\text{total-over-set } I \text{ } S = (\forall l \in S. \text{Pos } l \in I \vee \text{Neg } l \in I)$

definition *total-over-m* :: $'a \text{ literal set} \Rightarrow 'a \text{ clause set} \Rightarrow \text{bool}$ **where**
 $\text{total-over-m } I \text{ } \psi_s = \text{total-over-set } I \text{ } (\text{atms-of-ms } \psi_s)$

lemma *total-over-set-empty[simp]*:
 $\text{total-over-set } I \text{ } \{\}$
unfolding *total-over-set-def* **by** *auto*

lemma *total-over-m-empty[simp]*:
 $\text{total-over-m } I \text{ } \{\}$
unfolding *total-over-m-def* **by** *auto*

lemma *total-over-set-single[iff]*:
 $\text{total-over-set } I \text{ } \{L\} \longleftrightarrow (\text{Pos } L \in I \vee \text{Neg } L \in I)$
unfolding *total-over-set-def* **by** *auto*

lemma *total-over-set-insert[iff]*:
 $\text{total-over-set } I \text{ } (\text{insert } L \text{ } Ls) \longleftrightarrow ((\text{Pos } L \in I \vee \text{Neg } L \in I) \wedge \text{total-over-set } I \text{ } Ls)$
unfolding *total-over-set-def* **by** *auto*

lemma *total-over-set-union*[iff]:
 $total-over-set\ I\ (Ls \cup Ls') \longleftrightarrow (total-over-set\ I\ Ls \wedge total-over-set\ I\ Ls')$
unfolding *total-over-set-def* **by** *auto*

lemma *total-over-m-subset*:
 $A \subseteq B \implies total-over-m\ I\ B \implies total-over-m\ I\ A$
using *atms-of-ms-mono*[of *A*] **unfolding** *total-over-m-def* *total-over-set-def* **by** *auto*

lemma *total-over-m-sum*[iff]:
shows $total-over-m\ I\ \{C + D\} \longleftrightarrow (total-over-m\ I\ \{C\} \wedge total-over-m\ I\ \{D\})$
using *assms* **unfolding** *total-over-m-def* *total-over-set-def* **by** *auto*

lemma *total-over-m-union*[iff]:
 $total-over-m\ I\ (A \cup B) \longleftrightarrow (total-over-m\ I\ A \wedge total-over-m\ I\ B)$
unfolding *total-over-m-def* *total-over-set-def* **by** *auto*

lemma *total-over-m-insert*[iff]:
 $total-over-m\ I\ (insert\ a\ A) \longleftrightarrow (total-over-set\ I\ (atms-of\ a) \wedge total-over-m\ I\ A)$
unfolding *total-over-m-def* *total-over-set-def* **by** *fastforce*

lemma *total-over-m-extension*:
fixes $I :: 'v\ literal\ set$ **and** $A :: 'v\ clauses$
assumes *total*: $total-over-m\ I\ A$
shows $\exists I'. total-over-m\ (I \cup I')\ (A \cup B)$
 $\wedge (\forall x \in I'. atm-of\ x \in atms-of-ms\ B \wedge atm-of\ x \notin atms-of-ms\ A)$
proof –
let $?I' = \{Pos\ v \mid v. v \in atms-of-ms\ B \wedge v \notin atms-of-ms\ A\}$
have $(\forall x \in ?I'. atm-of\ x \in atms-of-ms\ B \wedge atm-of\ x \notin atms-of-ms\ A)$ **by** *auto*
moreover have $total-over-m\ (I \cup ?I')\ (A \cup B)$
using *total* **unfolding** *total-over-m-def* *total-over-set-def* **by** *auto*
ultimately show *?thesis* **by** *blast*
qed

lemma *total-over-m-consistent-extension*:
fixes $I :: 'v\ literal\ set$ **and** $A :: 'v\ clauses$
assumes *total*: $total-over-m\ I\ A$
and *cons*: $consistent-interp\ I$
shows $\exists I'. total-over-m\ (I \cup I')\ (A \cup B)$
 $\wedge (\forall x \in I'. atm-of\ x \in atms-of-ms\ B \wedge atm-of\ x \notin atms-of-ms\ A) \wedge consistent-interp\ (I \cup I')$
proof –
let $?I' = \{Pos\ v \mid v. v \in atms-of-ms\ B \wedge v \notin atms-of-ms\ A \wedge Pos\ v \notin I \wedge Neg\ v \notin I\}$
have $(\forall x \in ?I'. atm-of\ x \in atms-of-ms\ B \wedge atm-of\ x \notin atms-of-ms\ A)$ **by** *auto*
moreover have $total-over-m\ (I \cup ?I')\ (A \cup B)$
using *total* **unfolding** *total-over-m-def* *total-over-set-def* **by** *auto*
moreover have $consistent-interp\ (I \cup ?I')$
using *cons* **unfolding** *consistent-interp-def* **by** (*intro allI*) (*case-tac L, auto*)
ultimately show *?thesis* **by** *blast*
qed

lemma *total-over-set-atms-of*[simp]:
 $total-over-set\ Ia\ (atms-of-s\ Ia)$
unfolding *total-over-set-def* *atms-of-s-def* **by** (*metis image-iff literal.exhaust-sel*)

lemma *total-over-set-literal-defined*:
assumes $\{\#A\# \} + D \in \psi s$

and *total-over-set* I (*atms-of-ms* ψ s)
shows $A \in I \vee \neg A \in I$
using *assms* **unfolding** *total-over-set-def* **by** (*metis* (*no-types*) *Neg-atm-of-iff* *in-m-in-literals*
literal.collapse(1) *uminus-Neg* *uminus-Pos*)

lemma *tot-over-m-remove*:
assumes *total-over-m* ($I \cup \{L\}$) $\{\psi\}$
and $L: \neg L \in \# \psi \neg L \notin \# \psi$
shows *total-over-m* I $\{\psi\}$
unfolding *total-over-m-def* *total-over-set-def*

proof

fix l
assume $l: l \in \text{atms-of-ms } \{\psi\}$
then have $\text{Pos } l \in I \vee \text{Neg } l \in I \vee l = \text{atm-of } L$
using *assms* **unfolding** *total-over-m-def* *total-over-set-def* **by** *auto*
moreover have $\text{atm-of } L \notin \text{atms-of-ms } \{\psi\}$
proof (*rule ccontr*)
assume $\neg ?thesis$
then have $\text{atm-of } L \in \text{atms-of } \psi$ **by** *auto*
then have $\text{Pos } (\text{atm-of } L) \in \# \psi \vee \text{Neg } (\text{atm-of } L) \in \# \psi$
using *atm-imp-pos-or-neg-lit* **by** *metis*
then have $L \in \# \psi \vee \neg L \in \# \psi$ **by** (*case-tac* L) *auto*
then show *False* **using** L **by** *auto*
qed
ultimately show $\text{Pos } l \in I \vee \text{Neg } l \in I$ **using** l **by** *metis*
qed

lemma *total-union*:
assumes *total-over-m* I ψ
shows *total-over-m* ($I \cup I'$) ψ
using *assms* **unfolding** *total-over-m-def* *total-over-set-def* **by** *auto*

lemma *total-union-2*:
assumes *total-over-m* I ψ
and *total-over-m* I' ψ'
shows *total-over-m* ($I \cup I'$) ($\psi \cup \psi'$)
using *assms* **unfolding** *total-over-m-def* *total-over-set-def* **by** *auto*

11.2.4 Interpretations

definition *true-cls* :: $'a \text{ interp} \Rightarrow 'a \text{ clause} \Rightarrow \text{bool}$ (*infix* \models 50) **where**
 $I \models C \longleftrightarrow (\exists L \in \# C. I \models_l L)$

lemma *true-cls-empty*[*iff*]: $\neg I \models \{\#\}$
unfolding *true-cls-def* **by** *auto*

lemma *true-cls-singleton*[*iff*]: $I \models \{\#L\# \} \longleftrightarrow I \models_l L$
unfolding *true-cls-def* **by** (*auto* *split:split-if-asm*)

lemma *true-cls-union*[*iff*]: $I \models C + D \longleftrightarrow I \models C \vee I \models D$
unfolding *true-cls-def* **by** *auto*

lemma *true-cls-mono-set-mset*: $\text{set-mset } C \subseteq \text{set-mset } D \Longrightarrow I \models C \Longrightarrow I \models D$
unfolding *true-cls-def* *subset-eq* *Bex-mset-def* **by** (*metis* *mem-set-mset-iff*)

lemma *true-cls-mono-leD*[*dest*]: $A \subseteq \# B \Longrightarrow I \models A \Longrightarrow I \models B$

unfolding *true-cls-def* **by** *auto*

lemma

assumes $I \models \psi$
shows *true-cls-union-increase*[*simp*]: $I \cup I' \models \psi$
and *true-cls-union-increase'*[*simp*]: $I' \cup I \models \psi$
using *assms* **unfolding** *true-cls-def* **by** *auto*

lemma *true-cls-mono-set-mset-l*:

assumes $A \models \psi$
and $A \subseteq B$
shows $B \models \psi$
using *assms* **unfolding** *true-cls-def* **by** *auto*

lemma *true-cls-replicate-mset*[*iff*]: $I \models \text{replicate-mset } n \ L \longleftrightarrow n \neq 0 \wedge I \models_l L$
by (*induct n*) *auto*

lemma *true-cls-empty-entails*[*iff*]: $\neg \{\} \models N$
by (*auto simp add: true-cls-def*)

lemma *true-cls-not-in-remove*:

assumes $L \notin \# \chi$
and $I \cup \{L\} \models \chi$
shows $I \models \chi$
using *assms* **unfolding** *true-cls-def* **by** *auto*

definition *true-clss* :: '*a* *interp* \Rightarrow '*a* *clauses* \Rightarrow *bool* (**infix** \models_s 50) **where**
 $I \models_s CC \longleftrightarrow (\forall C \in CC. I \models C)$

lemma *true-clss-empty*[*simp*]: $I \models_s \{\}$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-singleton*[*iff*]: $I \models_s \{C\} \longleftrightarrow I \models C$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-empty-entails-empty*[*iff*]: $\{\} \models_s N \longleftrightarrow N = \{\}$
unfolding *true-clss-def* **by** (*auto simp add: true-cls-def*)

lemma *true-cls-insert-l* [*simp*]:
 $M \models A \implies \text{insert } L \ M \models A$
unfolding *true-cls-def* **by** *auto*

lemma *true-clss-union*[*iff*]: $I \models_s CC \cup DD \longleftrightarrow I \models_s CC \wedge I \models_s DD$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-insert*[*iff*]: $I \models_s \text{insert } C \ DD \longleftrightarrow I \models C \wedge I \models_s DD$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-mono*: $DD \subseteq CC \implies I \models_s CC \implies I \models_s DD$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-union-increase*[*simp*]:
assumes $I \models_s \psi$
shows $I \cup I' \models_s \psi$
using *assms* **unfolding** *true-clss-def* **by** *auto*

lemma *true-clss-union-increase'*[simp]:
assumes $I' \models_s \psi$
shows $I \cup I' \models_s \psi$
using *assms* **by** (auto simp add: true-clss-def)

lemma *true-clss-commute-l*:
 $(I \cup I' \models_s \psi) \longleftrightarrow (I' \cup I \models_s \psi)$
by (simp add: Un-commute)

lemma *model-remove*[simp]: $I \models_s N \implies I \models_s \text{Set.remove } a \ N$
by (simp add: true-clss-def)

lemma *model-remove-minus*[simp]: $I \models_s N \implies I \models_s N - A$
by (simp add: true-clss-def)

lemma *notin-vars-union-true-clss-true-clss*:
assumes $\forall x \in I'. \text{atm-of } x \notin \text{atms-of-ms } A$
and $\text{atms-of } L \subseteq \text{atms-of-ms } A$
and $I \cup I' \models L$
shows $I \models L$
using *assms* **unfolding** *true-clss-def true-lit-def Bex-mset-def*
by (metis Un-iff atm-of-lit-in-atms-of contra-subsetD)

lemma *notin-vars-union-true-clss-true-clss*:
assumes $\forall x \in I'. \text{atm-of } x \notin \text{atms-of-ms } A$
and $\text{atms-of-ms } L \subseteq \text{atms-of-ms } A$
and $I \cup I' \models_s L$
shows $I \models_s L$
using *assms* **unfolding** *true-clss-def true-lit-def Ball-def*
by (meson atms-of-atms-of-ms-mono notin-vars-union-true-clss-true-clss subset-trans)

11.2.5 Satisfiability

definition *satisfiable* :: 'a clause set \Rightarrow bool **where**
 $\text{satisfiable } CC \equiv \exists I. (I \models_s CC \wedge \text{consistent-interp } I \wedge \text{total-over-m } I \ CC)$

lemma *satisfiable-single*[simp]:
 $\text{satisfiable } \{\{\#L\#\}\}$
unfolding *satisfiable-def* **by** fastforce

abbreviation *unsatisfiable* :: 'a clause set \Rightarrow bool **where**
 $\text{unsatisfiable } CC \equiv \neg \text{satisfiable } CC$

lemma *satisfiable-decreasing*:
assumes $\text{satisfiable } (\psi \cup \psi')$
shows $\text{satisfiable } \psi$
using *assms* *total-over-m-union* **unfolding** *satisfiable-def* **by** blast

lemma *satisfiable-def-min*:
 $\text{satisfiable } CC$
 $\longleftrightarrow (\exists I. I \models_s CC \wedge \text{consistent-interp } I \wedge \text{total-over-m } I \ CC \wedge \text{atm-of } I = \text{atms-of-ms } CC)$
(is ?sat \longleftrightarrow ?B)

proof
assume ?B **then show** ?sat **by** (auto simp add: satisfiable-def)
next

```

assume ?sat
then obtain  $I$  where
   $I\text{-}CC: I \models_s CC$  and
   $cons: consistent\text{-}interp\ I$  and
   $tot: total\text{-}over\text{-}m\ I\ CC$ 
  unfolding  $satisfiable\text{-}def$  by  $auto$ 
let  $?I = \{P. P \in I \wedge atm\text{-}of\ P \in atm\text{-}of\text{-}ms\ CC\}$ 

have  $I\text{-}CC: ?I \models_s CC$ 
  using  $I\text{-}CC$  unfolding  $true\text{-}clss\text{-}def\ Ball\text{-}def\ true\text{-}cls\text{-}def\ Bex\text{-}mset\text{-}def\ true\text{-}lit\text{-}def$ 
  by ( $smt\ atm\text{-}of\text{-}lit\text{-}in\text{-}atms\text{-}of\ atm\text{-}of\text{-}atms\text{-}of\text{-}ms\text{-}mono\ mem\text{-}Collect\text{-}eq\ subset\text{-}eq$ )

moreover have  $cons: consistent\text{-}interp\ ?I$ 
  using  $cons$  unfolding  $consistent\text{-}interp\text{-}def$  by  $auto$ 
moreover have  $total\text{-}over\text{-}m\ ?I\ CC$ 
  using  $tot$  unfolding  $total\text{-}over\text{-}m\text{-}def\ total\text{-}over\text{-}set\text{-}def$  by  $auto$ 
moreover
  have  $atms\text{-}CC\text{-}incl: atm\text{-}of\text{-}ms\ CC \subseteq atm\text{-}of\text{-}I$ 
    using  $tot$  unfolding  $total\text{-}over\text{-}m\text{-}def\ total\text{-}over\text{-}set\text{-}def\ atm\text{-}of\text{-}ms\text{-}def$ 
    by ( $auto\ simp\ add: atm\text{-}of\text{-}def\ atm\text{-}of\text{-}s\text{-}def[symmetric]$ )
  have  $atm\text{-}of\text{-} ?I = atm\text{-}of\text{-}ms\ CC$ 
    using  $atms\text{-}CC\text{-}incl$  unfolding  $atms\text{-}of\text{-}ms\text{-}def$  by  $force$ 
ultimately show  $?B$  by  $auto$ 
qed

```

11.2.6 Entailment for Multisets of Clauses

definition $true\text{-}cls\text{-}mset :: 'a\ interp \Rightarrow 'a\ clause\ multiset \Rightarrow bool$ (**infix** \models_m 50) **where**
 $I \models_m CC \longleftrightarrow (\forall C \in \# CC. I \models C)$

lemma $true\text{-}cls\text{-}mset\text{-}empty[simp]: I \models_m \{\#\}$
unfolding $true\text{-}cls\text{-}mset\text{-}def$ **by** $auto$

lemma $true\text{-}cls\text{-}mset\text{-}singleton[iff]: I \models_m \{\#C\# \} \longleftrightarrow I \models C$
unfolding $true\text{-}cls\text{-}mset\text{-}def$ **by** ($auto\ split: split\text{-}if\text{-}asm$)

lemma $true\text{-}cls\text{-}mset\text{-}union[iff]: I \models_m CC + DD \longleftrightarrow I \models_m CC \wedge I \models_m DD$
unfolding $true\text{-}cls\text{-}mset\text{-}def$ **by** $fastforce$

lemma $true\text{-}cls\text{-}mset\text{-}image\text{-}mset[iff]: I \models_m image\text{-}mset\ f\ A \longleftrightarrow (\forall x \in \# A. I \models f\ x)$
unfolding $true\text{-}cls\text{-}mset\text{-}def$ **by** $fastforce$

lemma $true\text{-}cls\text{-}mset\text{-}mono: set\text{-}mset\ DD \subseteq set\text{-}mset\ CC \Longrightarrow I \models_m CC \Longrightarrow I \models_m DD$
unfolding $true\text{-}cls\text{-}mset\text{-}def\ subset\text{-}iff$ **by** $auto$

lemma $true\text{-}clss\text{-}set\text{-}mset[iff]: I \models_s set\text{-}mset\ CC \longleftrightarrow I \models_m CC$
unfolding $true\text{-}clss\text{-}def\ true\text{-}cls\text{-}mset\text{-}def$ **by** $auto$

lemma $true\text{-}cls\text{-}mset\text{-}increasing\text{-}r[simp]:$
 $I \models_m CC \Longrightarrow I \cup J \models_m CC$
unfolding $true\text{-}cls\text{-}mset\text{-}def$ **by** $auto$

theorem $true\text{-}cls\text{-}remove\text{-}unused:$
assumes $I \models \psi$
shows $\{v \in I. atm\text{-}of\ v \in atm\text{-}of\ \psi\} \models \psi$
using $assms$ **unfolding** $true\text{-}cls\text{-}def\ atm\text{-}of\text{-}def$ **by** $auto$

theorem *true-clss-remove-unused*:
assumes $I \models_s \psi$
shows $\{v \in I. \text{atm-of } v \in \text{atms-of-ms } \psi\} \models_s \psi$
unfolding *true-clss-def atms-of-def Ball-def*
proof (*intro allI impI*)
fix x
assume $x \in \psi$
then have $I \models x$
using *assms unfolding true-clss-def atms-of-def Ball-def* **by** *auto*

then have $\{v \in I. \text{atm-of } v \in \text{atms-of } x\} \models x$
by (*simp only: true-clss-remove-unused[of I]*)
moreover have $\{v \in I. \text{atm-of } v \in \text{atms-of } x\} \subseteq \{v \in I. \text{atm-of } v \in \text{atms-of-ms } \psi\}$
using $\langle x \in \psi \rangle$ **by** (*auto simp add: atms-of-ms-def*)
ultimately show $\{v \in I. \text{atm-of } v \in \text{atms-of-ms } \psi\} \models x$
using *true-clss-mono-set-mset-l* **by** *blast*
qed

A simple application of the previous theorem:

lemma *true-clss-union-decrease*:
assumes $II': I \cup I' \models \psi$
and $H: \forall v \in I'. \text{atm-of } v \notin \text{atms-of } \psi$
shows $I \models \psi$
proof –
let $?I = \{v \in I \cup I'. \text{atm-of } v \in \text{atms-of } \psi\}$
have $?I \models \psi$ **using** *true-clss-remove-unused II'* **by** *blast*
moreover have $?I \subseteq I$ **using** H **by** *auto*
ultimately show *?thesis* **using** *true-clss-mono-set-mset-l* **by** *blast*
qed

lemma *multiset-not-empty*:
assumes $M \neq \{\#\}$
and $x \in\# M$
shows $\exists A. x = \text{Pos } A \vee x = \text{Neg } A$
using *assms literal.exhaust-sel* **by** *blast*

lemma *atms-of-ms-empty*:
fixes $\psi :: 'v \text{ clauses}$
assumes $\text{atms-of-ms } \psi = \{\}$
shows $\psi = \{\} \vee \psi = \{\{\#\}\}$
using *assms* **by** (*auto simp add: atms-of-ms-def*)

lemma *consistent-interp-disjoint*:
assumes *consI: consistent-interp I*
and *disj: atms-of-s A \cap atms-of-s I = $\{\}$*
and *consA: consistent-interp A*
shows *consistent-interp (A \cup I)*
proof (*rule ccontr*)
assume $\neg ?thesis$
moreover have $\bigwedge L. \neg (L \in A \wedge \neg L \in I)$
using *disj unfolding atms-of-s-def* **by** (*auto simp add: rev-image-eqI*)
ultimately show *False*
using *consA consI unfolding consistent-interp-def* **by** (*metis (full-types) Un-iff literal.exhaust-sel uminus-Neg uminus-Pos*)

qed

lemma *total-remove-unused*:

assumes *total-over-m* $I \ \psi$
shows *total-over-m* $\{v \in I. \text{atm-of } v \in \text{atms-of-ms } \psi\} \ \psi$
using *assms unfolding total-over-m-def total-over-set-def*
by (*metis (lifting) literal.sel(1,2) mem-Collect-eq*)

lemma *true-cls-remove-hd-if-notin-vars*:

assumes *insert* $a \ M' \models D$
and *atm-of* $a \notin \text{atms-of } D$
shows $M' \models D$
using *assms by (auto simp add: atm-of-lit-in-atms-of true-cls-def)*

lemma *total-over-set-atm-of*:

fixes $I :: 'v \text{ interp}$ **and** $K :: 'v \text{ set}$
shows *total-over-set* $I \ K \longleftrightarrow (\forall l \in K. l \in (\text{atm-of } I))$
unfolding *total-over-set-def* **by** (*metis atms-of-s-def in-atms-of-s-decomp*)

11.2.7 Tautologies

definition *tautology* ($\psi :: 'v \text{ clause}$) $\equiv \forall I. \text{total-over-set } I \ (\text{atms-of } \psi) \longrightarrow I \models \psi$

lemma *tautology-Pos-Neg[intro]*:

assumes *Pos* $p \in \# A$ **and** *Neg* $p \in \# A$
shows *tautology* A
using *assms unfolding tautology-def total-over-set-def true-cls-def Bex-mset-def*
by (*meson atm-iff-pos-or-neg-lit true-lit-def*)

lemma *tautology-minus[simp]*:

assumes $L \in \# A$ **and** $-L \in \# A$
shows *tautology* A
by (*metis assms literal.exhaust tautology-Pos-Neg uminus-Neg uminus-Pos*)

lemma *tautology-exists-Pos-Neg*:

assumes *tautology* ψ
shows $\exists p. \text{Pos } p \in \# \psi \wedge \text{Neg } p \in \# \psi$

proof (*rule ccontr*)

assume $p: \neg (\exists p. \text{Pos } p \in \# \psi \wedge \text{Neg } p \in \# \psi)$
let $?I = \{-L \mid L. L \in \# \psi\}$
have *total-over-set* $?I \ (\text{atms-of } \psi)$
unfolding *total-over-set-def* **using** *atm-imp-pos-or-neg-lit* **by** *force*
moreover **have** $\neg ?I \models \psi$
unfolding *true-cls-def true-lit-def Bex-mset-def* **apply** *clarify*
using p **by** (*case-tac L*) *fastforce+*
ultimately show *False* **using** *assms unfolding tautology-def* **by** *auto*

qed

lemma *tautology-decomp*:

tautology $\psi \longleftrightarrow (\exists p. \text{Pos } p \in \# \psi \wedge \text{Neg } p \in \# \psi)$
using *tautology-exists-Pos-Neg* **by** *auto*

lemma *tautology-false[simp]*: $\neg \text{tautology } \{\#\}$

unfolding *tautology-def* **by** *auto*

lemma *tautology-add-single*:

tautology ($\{\#a\# \} + L$) \longleftrightarrow *tautology* $L \vee -a \in\# L$
unfolding *tautology-decomp* **by** (*cases a*) *auto*

lemma *minus-interp-tautology*:

assumes $\{-L \mid L. L \in\# \chi\} \models \chi$
shows *tautology* χ

proof –

obtain L **where** $L \in\# \chi \wedge -L \in\# \chi$
using *assms* **unfolding** *true-cls-def* **by** *auto*
then show *?thesis* **using** *tautology-decomp literal.exhaust uminus-Neg uminus-Pos* **by** *metis*
qed

lemma *remove-literal-in-model-tautology*:

assumes $I \cup \{Pos\ P\} \models \varphi$
and $I \cup \{Neg\ P\} \models \varphi$
shows $I \models \varphi \vee$ *tautology* φ
using *assms* **unfolding** *true-cls-def* **by** *auto*

lemma *tautology-imp-tautology*:

fixes $\chi\ \chi' :: 'v$ *clause*
assumes $\forall I. total-over-m\ I\ \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models \chi'$ **and** *tautology* χ
shows *tautology* χ' **unfolding** *tautology-def*

proof (*intro allI HOL.impI*)

fix $I :: 'v$ *literal set*
assume *totI*: *total-over-set* I (*atms-of* χ')
let $?I' = \{Pos\ v \mid v. v \in atms-of\ \chi \wedge v \notin atms-of-s\ I\}$
have *totI'*: *total-over-m* $(I \cup ?I')\ \{\chi\}$ **unfolding** *total-over-m-def total-over-set-def* **by** *auto*
then have $\chi: I \cup ?I' \models \chi$ **using** *assms(2)* **unfolding** *total-over-m-def tautology-def* **by** *simp*
then have $I \cup (?I' - I) \models \chi'$ **using** *assms(1)* *totI'* **by** *auto*
moreover have $\bigwedge L. L \in\# \chi' \Longrightarrow L \notin ?I'$
using *totI* **unfolding** *total-over-set-def* **by** (*auto dest: pos-lit-in-atms-of*)
ultimately show $I \models \chi'$ **unfolding** *true-cls-def* **by** *auto*

qed

11.2.8 Entailment for clauses and propositions

definition *true-cls-cls* :: $'a$ *clause* \Rightarrow $'a$ *clause* \Rightarrow *bool* (**infix** \models_f 49) **where**

$\psi \models_f \chi \longleftrightarrow (\forall I. total-over-m\ I\ (\{\psi\} \cup \{\chi\}) \longrightarrow consistent-interp\ I \longrightarrow I \models \psi \longrightarrow I \models \chi)$

definition *true-cls-clss* :: $'a$ *clause* \Rightarrow $'a$ *clauses* \Rightarrow *bool* (**infix** \models_{fs} 49) **where**

$\psi \models_{fs} \chi \longleftrightarrow (\forall I. total-over-m\ I\ (\{\psi\} \cup \chi) \longrightarrow consistent-interp\ I \longrightarrow I \models \psi \longrightarrow I \models_s \chi)$

definition *true-clss-cls* :: $'a$ *clauses* \Rightarrow $'a$ *clause* \Rightarrow *bool* (**infix** \models_p 49) **where**

$N \models_p \chi \longleftrightarrow (\forall I. total-over-m\ I\ (N \cup \{\chi\}) \longrightarrow consistent-interp\ I \longrightarrow I \models_s N \longrightarrow I \models \chi)$

definition *true-clss-clss* :: $'a$ *clauses* \Rightarrow $'a$ *clauses* \Rightarrow *bool* (**infix** \models_{ps} 49) **where**

$N \models_{ps} N' \longleftrightarrow (\forall I. total-over-m\ I\ (N \cup N') \longrightarrow consistent-interp\ I \longrightarrow I \models_s N \longrightarrow I \models_s N')$

lemma *true-cls-cls-refl[simp]*:

$A \models_f A$
unfolding *true-cls-cls-def* **by** *auto*

lemma *true-cls-cls-insert-l[simp]*:

$a \models_f C \Longrightarrow insert\ a\ A \models_p C$
unfolding *true-cls-cls-def true-clss-cls-def true-clss-def* **by** *fastforce*

lemma *true-cls-clss-empty*[iff]:
 $N \models_{fs} \{\}$
unfolding *true-cls-clss-def* **by** *auto*

lemma *true-prop-true-clause*[iff]:
 $\{\varphi\} \models_p \psi \iff \varphi \models_f \psi$
unfolding *true-cls-cls-def* *true-clss-cls-def* **by** *auto*

lemma *true-clss-clss-true-clss-cls*[iff]:
 $N \models_{ps} \{\psi\} \iff N \models_p \psi$
unfolding *true-clss-clss-def* *true-clss-cls-def* **by** *auto*

lemma *true-clss-clss-true-cls-clss*[iff]:
 $\{\chi\} \models_{ps} \psi \iff \chi \models_{fs} \psi$
unfolding *true-clss-clss-def* *true-cls-clss-def* **by** *auto*

lemma *true-clss-clss-empty*[simp]:
 $N \models_{ps} \{\}$
unfolding *true-clss-clss-def* **by** *auto*

lemma *true-clss-cls-subset*:
 $A \subseteq B \implies A \models_p CC \implies B \models_p CC$
unfolding *true-clss-cls-def* *total-over-m-union* **by** (*simp add: total-over-m-subset true-clss-mono*)

lemma *true-clss-cs-mono-l*[simp]:
 $A \models_p CC \implies A \cup B \models_p CC$
by (*auto intro: true-clss-cls-subset*)

lemma *true-clss-cs-mono-l2*[simp]:
 $B \models_p CC \implies A \cup B \models_p CC$
by (*auto intro: true-clss-cls-subset*)

lemma *true-clss-cls-mono-r*[simp]:
 $A \models_p CC \implies A \models_p CC + CC'$
unfolding *true-clss-cls-def* *total-over-m-union* *total-over-m-sum* **by** *blast*

lemma *true-clss-cls-mono-r'*[simp]:
 $A \models_p CC' \implies A \models_p CC + CC'$
unfolding *true-clss-cls-def* *total-over-m-union* *total-over-m-sum* **by** *blast*

lemma *true-clss-clss-union-l*[simp]:
 $A \models_{ps} CC \implies A \cup B \models_{ps} CC$
unfolding *true-clss-clss-def* *total-over-m-union* **by** *fastforce*

lemma *true-clss-clss-union-l-r*[simp]:
 $B \models_{ps} CC \implies A \cup B \models_{ps} CC$
unfolding *true-clss-clss-def* *total-over-m-union* **by** *fastforce*

lemma *true-clss-cls-in*[simp]:
 $CC \in A \implies A \models_p CC$
unfolding *true-clss-cls-def* *true-clss-def* *total-over-m-union* **by** *fastforce*

lemma *true-clss-cls-insert-l*[simp]:
 $A \models_p C \implies \text{insert } a \ A \models_p C$
unfolding *true-clss-cls-def* *true-clss-def* **using** *total-over-m-union*

by (metis Un-iff insert-is-Un sup commute)

lemma *true-clss-clss-insert-l[simp]*:

$A \models_{ps} C \implies \text{insert } a \ A \models_{ps} C$

unfolding *true-clss-clss-def true-clss-clss-def true-clss-def* **by** *blast*

lemma *true-clss-clss-union-and[iff]*:

$A \models_{ps} C \cup D \iff (A \models_{ps} C \wedge A \models_{ps} D)$

proof

```

{
  fix A C D :: 'a clauses
  assume A: A  $\models_{ps}$  C  $\cup$  D
  have A  $\models_{ps}$  C
    unfolding true-clss-clss-def true-clss-clss-def insert-def total-over-m-insert
  proof (intro allI impI)
    fix I
    assume totAC: total-over-m I (A  $\cup$  C)
    and cons: consistent-interp I
    and I: I  $\models_s$  A
    then have tot: total-over-m I A and tot': total-over-m I C by auto
    obtain I' where tot': total-over-m (I  $\cup$  I') (A  $\cup$  C  $\cup$  D)
    and cons': consistent-interp (I  $\cup$  I')
    and H:  $\forall x \in I'. \text{atm-of } x \in \text{atms-of-ms } D \wedge \text{atm-of } x \notin \text{atms-of-ms } (A \cup C)$ 
      using total-over-m-consistent-extension[OF - cons, of A  $\cup$  C] tot tot' by blast
    moreover have I  $\cup$  I'  $\models_s$  A using I by simp
    ultimately have I  $\cup$  I'  $\models_s$  C  $\cup$  D using A unfolding true-clss-clss-def by auto
    then have I  $\cup$  I'  $\models_s$  C  $\cup$  D by auto
    then show I  $\models_s$  C using notin-vars-union-true-clss-true-clss[of I'] H by auto
  qed
} note H = this
assume A  $\models_{ps}$  C  $\cup$  D
then show A  $\models_{ps}$  C  $\wedge$  A  $\models_{ps}$  D using H[of A] Un-commute[of C D] by metis
next
assume A  $\models_{ps}$  C  $\wedge$  A  $\models_{ps}$  D
then show A  $\models_{ps}$  C  $\cup$  D
  unfolding true-clss-clss-def by auto
qed

```

lemma *true-clss-clss-insert[iff]*:

$A \models_{ps} \text{insert } L \ Ls \iff (A \models_p L \wedge A \models_{ps} Ls)$

using *true-clss-clss-union-and*[of A {L} Ls] **by** *auto*

lemma *true-clss-clss-subset*:

$A \subseteq B \implies A \models_{ps} CC \implies B \models_{ps} CC$

by (metis subset-Un-eq true-clss-clss-union-l)

lemma *union-trus-clss-clss[simp]*: $A \cup B \models_{ps} B$

unfolding *true-clss-clss-def* **by** *auto*

lemma *true-clss-clss-remove[simp]*:

$A \models_{ps} B \implies A \models_{ps} B - C$

by (metis Un-Diff-Int true-clss-clss-union-and)

lemma *true-clss-clss-subsetE*:

$N \models_{ps} B \implies A \subseteq B \implies N \models_{ps} A$
by (*metis sup.orderE true-clss-clss-union-and*)

lemma *true-clss-clss-in-imp-true-clss-clss*:
assumes $N \models_{ps} U$
and $A \in U$
shows $N \models_p A$
using *assms mk-disjoint-insert* **by** *fastforce*

lemma *all-in-true-clss-clss*: $\forall x \in B. x \in A \implies A \models_{ps} B$
unfolding *true-clss-clss-def true-clss-def* **by** *auto*

lemma *true-clss-clss-left-right*:
assumes $A \models_{ps} B$
and $A \cup B \models_{ps} M$
shows $A \models_{ps} M \cup B$
using *assms* **unfolding** *true-clss-clss-def* **by** *auto*

lemma *true-clss-clss-generalise-true-clss-clss*:
 $A \cup C \models_{ps} D \implies B \models_{ps} C \implies A \cup B \models_{ps} D$

proof –

assume $a1: A \cup C \models_{ps} D$
assume $B \models_{ps} C$
then have $f2: \bigwedge M. M \cup B \models_{ps} C$
by (*meson true-clss-clss-union-l-r*)
have $\bigwedge M. C \cup (M \cup A) \models_{ps} D$
using $a1$ **by** (*simp add: Un-commute sup-left-commute*)
then show *?thesis*
using $f2$ **by** (*metis (no-types) Un-commute true-clss-clss-left-right true-clss-clss-union-and*)

qed

lemma *true-clss-clss-or-true-clss-clss-or-not-true-clss-clss-or*:

assumes $D: N \models_p D + \{\#- L\# \}$
and $C: N \models_p C + \{\#L\# \}$
shows $N \models_p D + C$
unfolding *true-clss-clss-def*

proof (*intro allI impI*)

fix I
assume *tot*: *total-over-m* $I (N \cup \{D + C\})$
and *consistent-interp* I
and $I \models_s N$
{
assume $L: L \in I \vee -L \in I$
then have *total-over-m* $I \{D + \{\#- L\# \}\}$
using *tot* **by** (*cases L*) *auto*
then have $I \models D + \{\#- L\# \}$ **using** $D \langle I \models_s N \rangle$ *tot* \langle *consistent-interp* $I \rangle$
unfolding *true-clss-clss-def* **by** *auto*
moreover
have *total-over-m* $I \{C + \{\#L\# \}\}$
using L *tot* **by** (*cases L*) *auto*
then have $I \models C + \{\#L\# \}$
using $C \langle I \models_s N \rangle$ *tot* \langle *consistent-interp* $I \rangle$ **unfolding** *true-clss-clss-def* **by** *auto*
ultimately have $I \models D + C$ **using** \langle *consistent-interp* $I \rangle$ *consistent-interp-def* **by** *fastforce*
}
moreover {

```

assume  $L: L \notin I \wedge -L \notin I$ 
let  $?I' = I \cup \{L\}$ 
have consistent-interp  $?I'$  using  $L \langle \text{consistent-interp } I \rangle$  by auto
moreover have total-over-m  $?I' \{D + \{\#- L\#\}\}$ 
  using tot unfolding total-over-m-def total-over-set-def by (auto simp add: atms-of-def)
moreover have total-over-m  $?I' N$  using tot using total-union by blast
moreover have  $?I' \models_s N$  using  $\langle I \models_s N \rangle$  using true-clss-union-increase by blast
ultimately have  $?I' \models D + \{\#- L\#\}$ 
  using  $D$  unfolding true-clss-cls-def by blast
then have  $?I' \models D$  using  $L$  by auto
moreover
  have total-over-set  $I$  (atms-of  $(D + C)$ ) using tot by auto
  then have  $L \notin \# D \wedge -L \notin \# D$ 
    using  $L$  unfolding total-over-set-def atms-of-def by (cases L) force+
  ultimately have  $I \models D + C$  unfolding true-cls-def by auto
}
ultimately show  $I \models D + C$  by blast
qed

```

lemma *atms-of-union-mset[simp]*:

atms-of $(A \# \cup B) = \text{atms-of } A \cup \text{atms-of } B$

unfolding *atms-of-def* **by** (*auto simp: max-def split: split-if-asm*)

lemma *true-cls-union-mset[iff]*: $I \models C \# \cup D \longleftrightarrow I \models C \vee I \models D$

unfolding *true-cls-def* **by** (*force simp: max-def Bex-mset-def split: split-if-asm*)

lemma *true-clss-cls-union-mset-true-clss-cls-or-not-true-clss-cls-or*:

assumes $D: N \models_p D + \{\#- L\#\}$

and $C: N \models_p C + \{\#L\#\}$

shows $N \models_p D \# \cup C$

unfolding *true-clss-cls-def*

proof (*intro allI impI*)

fix I

assume *tot: total-over-m* I $(N \cup \{D \# \cup C\})$

and *consistent-interp* I

and $I \models_s N$

{

assume $L: L \in I \vee -L \in I$

then **have** *total-over-m* $I \{D + \{\#- L\#\}\}$

using *tot* **by** (*cases L*) *auto*

then **have** $I \models D + \{\#- L\#\}$ **using** $D \langle I \models_s N \rangle$ *tot* $\langle \text{consistent-interp } I \rangle$

unfolding *true-clss-cls-def* **by** *auto*

moreover

have *total-over-m* $I \{C + \{\#L\#\}\}$

using L *tot* **by** (*cases L*) *auto*

then **have** $I \models C + \{\#L\#\}$

using $C \langle I \models_s N \rangle$ *tot* $\langle \text{consistent-interp } I \rangle$ **unfolding** *true-clss-cls-def* **by** *auto*

ultimately **have** $I \models D \# \cup C$ **using** $\langle \text{consistent-interp } I \rangle$ **unfolding** *consistent-interp-def* **by** *auto*

}

moreover {

assume $L: L \notin I \wedge -L \notin I$

let $?I' = I \cup \{L\}$

have *consistent-interp* $?I'$ **using** $L \langle \text{consistent-interp } I \rangle$ **by** *auto*

moreover have *total-over-m* $?I' \{D + \{\#- L\#\}\}$
using *tot unfolding total-over-m-def total-over-set-def* **by** (*auto simp add: atms-of-def*)
moreover have *total-over-m* $?I' N$ **using** *tot using total-union* **by** *blast*
moreover have $?I' \models_s N$ **using** $\langle I \models_s N \rangle$ **using** *true-clss-union-increase* **by** *blast*
ultimately have $?I' \models D + \{\#- L\#\}$
using *D unfolding true-clss-cls-def* **by** *blast*
then have $?I' \models D$ **using** *L* **by** *auto*
moreover
have *total-over-set* I (*atms-of* ($D + C$)) **using** *tot* **by** *auto*
then have $L \notin \# D \wedge -L \notin \# D$
using *L unfolding total-over-set-def atms-of-def* **by** (*cases L*) *force+*
ultimately have $I \models D \# \cup C$ **unfolding** *true-cls-def* **by** *auto*
}
ultimately show $I \models D \# \cup C$ **by** *blast*
qed

lemma *satisfiable-carac[iff]*:

$(\exists I. \text{consistent-interp } I \wedge I \models_s \varphi) \longleftrightarrow \text{satisfiable } \varphi$ (**is** $(\exists I. ?Q I) \longleftrightarrow ?S$)

proof

assume $?S$

then show $\exists I. ?Q I$ **unfolding** *satisfiable-def* **by** *auto*

next

assume $\exists I. ?Q I$

then obtain I **where** *cons: consistent-interp I* **and** $I: I \models_s \varphi$ **by** *metis*

let $?I' = \{Pos\ v \mid v. v \notin \text{atms-of-s } I \wedge v \in \text{atms-of-ms } \varphi\}$

have *consistent-interp* $(I \cup ?I')$

using *cons unfolding consistent-interp-def* **by** (*intro allI*) (*case-tac L, auto*)

moreover have *total-over-m* $(I \cup ?I') \varphi$

unfolding *total-over-m-def total-over-set-def* **by** *auto*

moreover have $I \cup ?I' \models_s \varphi$

using *I unfolding Ball-def true-clss-def true-cls-def* **by** *auto*

ultimately show $?S$ **unfolding** *satisfiable-def* **by** *blast*

qed

lemma *satisfiable-carac[simp]*: *consistent-interp* $I \implies I \models_s \varphi \implies \text{satisfiable } \varphi$

using *satisfiable-carac* **by** *metis*

11.3 Subsumptions

lemma *subsumption-total-over-m*:

assumes $A \subseteq \# B$

shows *total-over-m* $I \{B\} \implies \text{total-over-m } I \{A\}$

using *assms unfolding subset-mset-def total-over-m-def total-over-set-def*

by (*auto simp add: mset-le-exists-conv*)

lemma *atm-of-eq-atm-of*:

atm-of $L = \text{atm-of } L' \longleftrightarrow (L = L' \vee L = -L')$

by (*cases L; cases L'*) *auto*

lemma *atms-of-replicate-mset-replicate-mset-uminus[simp]*:

atms-of $(D - \text{replicate-mset } (\text{count } D\ L)\ L - \text{replicate-mset } (\text{count } D\ (-L))\ (-L))$

$= \text{atms-of } D - \{\text{atm-of } L\}$

by (*auto split: split-if-asm simp add: atm-of-eq-atm-of atms-of-def*)

lemma *subsumption-chained*:

assumes $\forall I. \text{total-over-m } I \{D\} \longrightarrow I \models D \longrightarrow I \models \varphi$

```

and  $C \subseteq\# D$ 
shows  $(\forall I. \text{total-over-}m\ I\ \{C\} \longrightarrow I \models C \longrightarrow I \models \varphi) \vee \text{tautology}\ \varphi$ 
using assms
proof (induct card  $\{Pos\ v \mid v. v \in \text{atms-of}\ D \wedge v \notin \text{atms-of}\ C\}$  arbitrary: D
  rule: nat-less-induct-case)
case 0 note  $n = \text{this}(1)$  and  $H = \text{this}(2)$  and  $incl = \text{this}(3)$ 
then have  $\text{atms-of}\ D \subseteq \text{atms-of}\ C$  by auto
then have  $\forall I. \text{total-over-}m\ I\ \{C\} \longrightarrow \text{total-over-}m\ I\ \{D\}$ 
  unfolding total-over-}m-def total-over-set-def by auto
moreover have  $\forall I. I \models C \longrightarrow I \models D$  using incl true-cls-mono-leD by blast
ultimately show ?case using H by auto
next
case (Suc  $n\ D$ ) note  $IH = \text{this}(1)$  and  $\text{card} = \text{this}(2)$  and  $H = \text{this}(3)$  and  $incl = \text{this}(4)$ 
let  $?atms = \{Pos\ v \mid v. v \in \text{atms-of}\ D \wedge v \notin \text{atms-of}\ C\}$ 
have finite  $?atms$  by auto
then obtain L where  $L: L \in ?atms$ 
  using card by (metis (no-types, lifting) Collect-empty-eq card-0-eq mem-Collect-eq
    nat.simps(3))
let  $?D' = D - \text{replicate-mset}\ (\text{count}\ D\ L)\ L - \text{replicate-mset}\ (\text{count}\ D\ (-L))\ (-L)$ 
have  $\text{atms-of-}D: \text{atms-of-}ms\ \{D\} \subseteq \text{atms-of-}ms\ \{?D'\} \cup \{\text{atm-of}\ L\}$  by auto

{
  fix I
  assume  $\text{total-over-}m\ I\ \{?D'\}$ 
  then have tot:  $\text{total-over-}m\ (I \cup \{L\})\ \{D\}$ 
    unfolding total-over-}m-def total-over-set-def using atms-of-D by auto

  assume IDL:  $I \models ?D'$ 
  then have  $I \cup \{L\} \models D$  unfolding true-cls-def by force
  then have  $I \cup \{L\} \models \varphi$  using H tot by auto

  moreover
  have tot':  $\text{total-over-}m\ (I \cup \{-L\})\ \{D\}$ 
    using tot unfolding total-over-}m-def total-over-set-def by auto
  have  $I \cup \{-L\} \models D$  using IDL unfolding true-cls-def by force
  then have  $I \cup \{-L\} \models \varphi$  using H tot' by auto
  ultimately have  $I \models \varphi \vee \text{tautology}\ \varphi$ 
    using L remove-literal-in-model-tautology by force
} note  $H' = \text{this}$ 

have  $L \notin\# C$  and  $-L \notin\# C$  using L atm-iff-pos-or-neg-lit by force+
then have C-in-D':  $C \subseteq\# ?D'$  using  $\langle C \subseteq\# D \rangle$  by (auto simp add: subseteq-mset-def)
have  $\text{card}\ \{Pos\ v \mid v. v \in \text{atms-of}\ ?D' \wedge v \notin \text{atms-of}\ C\} <$ 
   $\text{card}\ \{Pos\ v \mid v. v \in \text{atms-of}\ D \wedge v \notin \text{atms-of}\ C\}$ 
  using L by (auto intro!: psubset-card-mono)
then show ?case
  using IH C-in-D' H' unfolding card[symmetric] by blast
qed

```

11.4 Removing Duplicates

lemma *tautology-remdups-mset[iff]*:

tautology (*remdups-mset* *C*) \longleftrightarrow *tautology* *C*

unfolding *tautology-decomp* by *auto*

lemma *atms-of-remdups-mset[simp]*: *atms-of* (*remdups-mset* *C*) = *atms-of* *C*

unfolding *atms-of-def* **by** *auto*

lemma *true-cls-remdups-mset*[*iff*]: $I \models \text{remdups-mset } C \longleftrightarrow I \models C$
unfolding *true-cls-def* **by** *auto*

lemma *true-clss-cls-remdups-mset*[*iff*]: $A \models_p \text{remdups-mset } C \longleftrightarrow A \models_p C$
unfolding *true-clss-cls-def total-over-m-def* **by** *auto*

11.5 Set of all Simple Clauses

A simple clause contains no duplicate and is not tautology.

function *build-all-simple-clss* :: '*v* :: linorder set \Rightarrow '*v* clause set **where**
build-all-simple-clss *vars* =
 (if $\neg \text{finite } \text{vars} \vee \text{vars} = \{\}$
 then $\{\{\#\}\}$
 else
 let *cls'* = *build-all-simple-clss* (*vars* - {*Min vars*}) in
 $\{\{\#Pos (Min \text{ vars})\# \} + \chi \mid \chi. \chi \in \text{cls}'\} \cup$
 $\{\{\#Neg (Min \text{ vars})\# \} + \chi \mid \chi. \chi \in \text{cls}'\} \cup$
 cls')
by *auto*
termination by (*relation measure card*) (*auto simp add: card-gt-0-iff*)

To avoid infinite simplifier loops:

declare *build-all-simple-clss.simps*[*simp del*]

lemma *build-all-simple-clss-simps-if*[*simp*]:
 $\neg \text{finite } \text{vars} \vee \text{vars} = \{\} \implies \text{build-all-simple-clss } \text{vars} = \{\{\#\}\}$
by (*simp add: build-all-simple-clss.simps*)

lemma *build-all-simple-clss-simps-else*[*simp*]:
fixes *vars*::'*v* ::linorder set
defines *cls* \equiv *build-all-simple-clss* (*vars* - {*Min vars*})
shows
 $\text{finite } \text{vars} \wedge \text{vars} \neq \{\} \implies \text{build-all-simple-clss } (\text{vars}::'\text{v}::\text{linorder set}) =$
 $\{\{\#Pos (Min \text{ vars})\# \} + \chi \mid \chi. \chi \in \text{cls}\}$
 $\cup \{\{\#Neg (Min \text{ vars})\# \} + \chi \mid \chi. \chi \in \text{cls}\}$
 $\cup \text{cls}$
using *build-all-simple-clss.simps*[*of vars*] **unfolding** *Let-def cls-def* **by** *metis*

lemma *build-all-simple-clss-finite*:
fixes *atms*::'*v*::linorder set
shows *finite* (*build-all-simple-clss* *atms*)
proof (*induct card atms arbitrary: atms rule: nat-less-induct*)
case (*1 atms*) **note** *IH* = *this*
 {
 assume *atms* = $\{\}$ $\vee \neg \text{finite } \text{atms}$
 then have *finite* (*build-all-simple-clss* *atms*) **by** *auto*
 }
moreover {
 assume *atms*: *atms* $\neq \{\}$ **and** *fin*: *finite* *atms*
 then have *Min atms* \in *atms* **using** *Min-in* **by** *auto*
 then have *card* (*atms* - {*Min atms*}) $<$ *card atms* **using** *fin atms* **by** (*meson card-Diff1-less*)
 then have *finite* (*build-all-simple-clss* (*atms* - {*Min atms*})) **using** *IH* **by** *auto*
 then have *finite* (*build-all-simple-clss* *atms*) **by** (*simp add: atms fin*)
 }

```

}
ultimately show finite (build-all-simple-clss atms) by blast
qed

```

lemma *build-all-simple-clssE*:

```

assumes
  x ∈ build-all-simple-clss atms and
  finite atms
shows atms-of x ⊆ atms ∧ ¬tautology x ∧ distinct-mset x
using assms
proof (induct card atms arbitrary: atms x)
  case (0 atms)
  then show ?case by auto
next
  case (Suc n) note IH = this(1) and card = this(2) and x = this(3) and finite = this(4)
  obtain v where v ∈ atms and v: v = Min atms
  using Min-in card local.finite by fastforce

  let ?atms' = atms - {v}
  have build-all-simple-clss atms
    = {{#Pos v#} + χ |χ. χ ∈ build-all-simple-clss (?atms')}
      ∪ {{#Neg v#} + χ |χ. χ ∈ build-all-simple-clss (?atms')}
      ∪ build-all-simple-clss (?atms')
  using build-all-simple-clss-simps-else[of atms] finite ⟨v ∈ atms⟩ unfolding v
  by (metis emptyE)
  then consider
    (Pos) χ φ where x = {#φ#} + χ and χ ∈ build-all-simple-clss (?atms') and
    φ = Pos v ∨ φ = Neg v
  | (In) x ∈ build-all-simple-clss (?atms')
  using x by auto
  then show ?case
  proof cases
    case In
    then show ?thesis using card finite IH[of ?atms'] ⟨v ∈ atms⟩ by fastforce
  next
    case Pos note x-χ = this(1) and χ = this(2) and φ = this(3)
    have
      atms-of χ ⊆ atms - {v} and
      ¬ tautology χ and
      distinct-mset χ
    using card finite IH[of ?atms' χ] ⟨v ∈ atms⟩ x-χ χ by auto
    moreover then have count χ (Neg v) = 0
    using ⟨v ∈ atms⟩ unfolding x-χ by (metis Diff-insert-absorb Set.set-insert
      atm-iff-pos-or-neg-lit grOI subset-iff)
    moreover have count χ (Pos v) = 0
    using ⟨atms-of χ ⊆ atms - {v}⟩ by (meson Diff-iff atm-iff-pos-or-neg-lit
      contra-subsetD insertI1 not-gr0)
    ultimately show ?thesis
    using ⟨v ∈ atms⟩ φ unfolding x-χ
    by (auto simp add: tautology-add-single distinct-mset-add-single)
  qed
qed

```

lemma *cls-in-build-all-simple-clss*:

shows {#} ∈ build-all-simple-clss s

```

by (induct s rule: build-all-simple-clss.induct)
(metis (no-types, lifting) UnCI build-all-simple-clss.simps insertI1)

lemma build-all-simple-clss-card:
  fixes atms :: 'v :: linorder set
  assumes finite atms
  shows card (build-all-simple-clss atms)  $\leq 3^{\wedge}(\text{card atms})$ 
  using assms
proof (induct card atms arbitrary: atms rule: nat-less-induct)
  case (1 atms) note IH = this(1) and finite = this(2)
  {
    assume atms = {}
    then have card (build-all-simple-clss atms)  $\leq 3^{\wedge}(\text{card atms})$  by auto
  }
  moreover {
    let ?P = {{#Pos (Min atms)#} +  $\chi$  |  $\chi. \chi \in \text{build-all-simple-clss (atms - \{Min atms\})}$ }
    let ?N = {{#Neg (Min atms)#} +  $\chi$  |  $\chi. \chi \in \text{build-all-simple-clss (atms - \{Min atms\})}$ }
    let ?Z = build-all-simple-clss (atms - {Min atms})
    assume atms: atms  $\neq \{\}$ 
    then have min: Min atms  $\in$  atms using Min-in finite by auto
    then have card-atms-1: card atms  $\geq 1$  by (simp add: Suc-leI atms card-gt-0-iff local.finite)
    have card (build-all-simple-clss atms) = card (?P  $\cup$  ?N  $\cup$  ?Z) using atms finite by simp
    moreover
      have  $\bigwedge M Ma. \text{card } ((M::'v \text{ literal multiset set}) \cup Ma) \leq \text{card } Ma + \text{card } M$ 
        by (simp add: add commute card-Un-le)
      then have card (?P  $\cup$  ?N  $\cup$  ?Z)  $\leq$  card ?Z + (card ?P + card ?N)
        by (meson Nat.le-trans card-Un-le nat-add-left-cancel-le)
      then have card (?P  $\cup$  ?N  $\cup$  ?Z)  $\leq$  card ?P + card ?N + card ?Z

      by presburger
    also
      have PZ: card ?P  $\leq$  card ?Z
        by (simp add: Setcompr-eq-image build-all-simple-clss-finite card-image-le)
      have NZ: card ?N  $\leq$  card ?Z
        by (simp add: Setcompr-eq-image build-all-simple-clss-finite card-image-le)
      have card ?P + card ?N + card ?Z  $\leq$  card ?Z + card ?Z + card ?Z
        using PZ NZ by linarith
      finally have card (build-all-simple-clss atms)  $\leq$  card ?Z + card ?Z + card ?Z .
    moreover
      have finite': finite (atms - {Min atms}) and
        card: card (atms - {Min atms}) = card atms - 1
        using finite min by auto
      have card-inf: card (atms - {Min atms})  $<$  card atms
        using card (card atms  $\geq 1$ ) min by auto
      then have card ?Z  $\leq 3^{\wedge}(\text{card atms} - 1)$  using IH finite' card by metis
    moreover
      have  $(3::\text{nat})^{\wedge}(\text{card atms} - 1) + 3^{\wedge}(\text{card atms} - 1) + 3^{\wedge}(\text{card atms} - 1)$ 
        =  $3 * 3^{\wedge}(\text{card atms} - 1)$  by simp
      then have  $(3::\text{nat})^{\wedge}(\text{card atms} - 1) + 3^{\wedge}(\text{card atms} - 1) + 3^{\wedge}(\text{card atms} - 1)$ 
        =  $3^{\wedge}(\text{card atms})$  by (metis card card-Suc-Diff1 local.finite min power-Suc)
      ultimately have card (build-all-simple-clss atms)  $\leq 3^{\wedge}(\text{card atms})$  by linarith
  }
  ultimately show card (build-all-simple-clss atms)  $\leq 3^{\wedge}(\text{card atms})$  by metis
qed

```

lemma *build-all-simple-clss-mono-disj*:

assumes $atms \cap atms' = \{\}$ **and** *finite* $atms$ **and** *finite* $atms'$

shows $build-all-simple-clss\ atms \subseteq build-all-simple-clss\ (atms \cup atms')$

using *assms*

proof (*induct card (atms \cup atms')* *arbitrary: atms atms'*)

case ($0\ atms'\ atms$)

then show *?case* **by** *auto*

next

case ($Suc\ n\ atms\ atms'$) **note** $IH = this(1)$ **and** $c = this(2)$ **and** $disj = this(3)$ **and** $finite = this(4)$

and $finite' = this(5)$

let $?min = Min\ (atms \cup atms')$

have $m: ?min \in atms \vee ?min \in atms'$ **by** (*metis Min-in Un-iff c card-eq-0-iff nat.distinct(1)*)

moreover {

assume $min: ?min \in atms'$

then have $min': ?min \notin atms$ **using** *disj* **by** *auto*

then have $atms = atms - \{?min\}$ **by** *fastforce*

then have $n = card\ (atms \cup (atms' - \{?min\}))$

using $c\ min\ finite\ finite'$ **by** (*metis Min-in Un-Diff card-Diff-singleton-if diff-Suc-1 finite-UnI sup-eq-bot-iff*)

moreover have $atms \cap (atms' - \{?min\}) = \{\}$ **using** *disj* **by** *auto*

moreover have $finite\ (atms' - \{?min\})$ **using** $finite'$ **by** *auto*

ultimately have $build-all-simple-clss\ atms \subseteq build-all-simple-clss\ (atms \cup (atms' - \{?min\}))$

using $IH[of\ atms\ atms' - \{?min\}]\ finite$ **by** *metis*

moreover have $atms \cup (atms' - \{?min\}) = (atms \cup atms') - \{?min\}$ **using** $min\ min'$ **by** *auto*

ultimately have *?case* **by** (*metis (no-types, lifting) build-all-simple-clss.simps c card-0-eq finite' finite-UnI le-supI2 local.finite nat.distinct(1)*)

}

moreover {

let $?atms' = atms - \{Min\ atms\}$

assume $min: ?min \in atms$

moreover have $min': ?min \notin atms'$ **using** *disj min* **by** *auto*

moreover have $atms' - \{?min\} = atms'$

using $\langle ?min \notin atms' \rangle$ **by** *fastforce*

ultimately have $n = card\ (atms - \{?min\} \cup atms')$

by (*metis Min-in Un-Diff c card-0-eq card-Diff-singleton-if diff-Suc-1 finite' finite-UnI finite nat.distinct(1)*)

moreover have $finite\ (atms - \{?min\})$ **using** $finite$ **by** *auto*

moreover have $(atms - \{?min\}) \cap atms' = \{\}$ **using** *disj* **by** *auto*

ultimately have $build-all-simple-clss\ (atms - \{?min\})$

$\subseteq build-all-simple-clss\ ((atms - \{?min\}) \cup atms')$

using $IH[of\ atms - \{?min\}\ atms']\ finite'$ **by** *metis*

moreover have $build-all-simple-clss\ atms$

$= \{\{\#Pos\ (Min\ atms)\#\} + \chi \mid \chi. \chi \in build-all-simple-clss\ (?atms')\}$

$\cup \{\{\#Neg\ (Min\ atms)\#\} + \chi \mid \chi. \chi \in build-all-simple-clss\ (?atms')\}$

$\cup build-all-simple-clss\ (?atms')$

using $build-all-simple-clss-simps-else[of\ atms]\ finite\ min$ **by** (*metis emptyE*)

moreover

let $?mcls = build-all-simple-clss\ (atms \cup atms' - \{?min\})$

have $build-all-simple-clss\ (atms \cup atms')$

$= \{\{\#Pos\ (?min)\#\} + \chi \mid \chi. \chi \in ?mcls\} \cup \{\{\#Neg\ (?min)\#\} + \chi \mid \chi. \chi \in ?mcls\} \cup ?mcls$

using $build-all-simple-clss-simps-else[of\ atms \cup atms']\ finite'\ min$

by (*metis c card-eq-0-iff nat.distinct(1)*)

moreover have $atms \cup atms' - \{?min\} = atms - \{?min\} \cup atms'$

using $min\ min'$ **by** (*simp add: Un-Diff*)

moreover have $Min\ atms = ?min$ **using** $min\ min'$ **by** (*simp add: Min-eqI finite' local.finite*)


```

    ultimately have ?case by auto
  }
  ultimately show ?case by metis
qed

```

lemma *build-all-simple-clss-mono*:

assumes *finite*: *finite* *atms'* **and** *incl*: $atms \subseteq atms'$
shows *build-all-simple-clss* $atms \subseteq build-all-simple-clss\ atms'$

proof –

have $atms' = atms \cup (atms' - atms)$ **using** *incl* **by** *auto*
moreover **have** *finite* $(atms' - atms)$ **using** *finite* **by** *auto*
moreover **have** $atms \cap (atms' - atms) = \{\}$ **by** *auto*
ultimately show ?thesis
using *rev-finite-subset*[*OF* *assms*] *build-all-simple-clss-mono-disj* **by** (*metis* (*no-types*))

qed

lemma *distinct-mset-not-tautology-implies-in-build-all-simple-clss*:

assumes *distinct-mset* χ **and** \neg *tautology* χ
shows $\chi \in build-all-simple-clss\ (atms-of\ \chi)$
using *assms*

proof (*induct* *card* (*atms-of* χ) *arbitrary*: χ)

case 0

then show ?case **by** *simp*

next

case (*Suc* *n*) **note** *IH* = *this*(1) **and** *simp* = *this*(3) **and** *c* = *this*(2) **and** *no-dup* = *this*(4)

have *finite*: *finite* (*atms-of* χ) **by** *simp*

with *no-dup* *atm-iff-pos-or-neg-lit* **obtain** *L* **where**

L χ : $L \in \# \chi$ **and**

L-min: *atm-of* *L* = *Min* (*atms-of* χ) **and**

mL χ : $\neg \neg L \in \# \chi$

by (*metis* *Min-in c card-0-eq literal.sel*(1,2) *nat.distinct*(1) *tautology-minus*)

then have χL : $\chi = (\chi - \{\#L\}) + \{\#L\}$ **by** *auto*

have *atm* χ : *atms-of* $\chi = atms-of\ (\chi - \{\#L\}) \cup \{atm-of\ L\}$

using *arg-cong*[*OF* χL , *of atms-of*] **by** *simp*

have *a* χ : *atms-of* $(\chi - \{\#L\}) = (atms-of\ \chi) - \{atm-of\ L\}$

proof (*standard*, *standard*)

fix *v*

assume *a*: $v \in atms-of\ (\chi - \{\#L\})$

then obtain *l* **where** *l*: $v = atm-of\ l$ **and** *l'*: $l \in \# \chi - \{\#L\}$

unfolding *atms-of-def* **by** *auto*

moreover {

assume $v = atm-of\ L$

then have $L \in \# \chi - \{\#L\} \vee \neg L \in \# \chi - \{\#L\}$

using *l' l* **by** (*auto simp add: atm-of-eq-atm-of*)

moreover have $L \notin \# \chi - \{\#L\}$ **using** $\langle L \in \# \chi \rangle$ *simp* **unfolding** *distinct-mset-def* **by** *auto*

ultimately have *False* **using** *mL* χ **by** *auto*

}

ultimately show $v \in atms-of\ \chi - \{atm-of\ L\}$

by (*auto dest: atm-of-lit-in-atms-of split: split-if-asm*)

next

show *atms-of* $\chi - \{atm-of\ L\} \subseteq atms-of\ (\chi - \{\#L\})$ **using** *atm* χ **by** *auto*

qed

```

let ?s' = build-all-simple-clss (atms-of ( $\chi - \{\#L\# \}$ ))
have card (atms-of ( $\chi - \{\#L\# \}$ )) = n
  using c finite a $\chi$  by (simp add: L $\chi$  atm-of-lit-in-atms-of)
moreover have distinct-mset ( $\chi - \{\#L\# \}$ ) using simp by auto
moreover have  $\neg$ tautology ( $\chi - \{\#L\# \}$ )
  by (meson Multiset.diff-le-self mset-leD no-dup tautology-decomp)
ultimately have  $\chi$ in:  $\chi - \{\#L\# \} \in \text{build-all-simple-clss (atms-of ( $\chi - \{\#L\# \}$ ))}$ 
  using IH by simp
have  $\chi = \{\#L\# \} + (\chi - \{\#L\# \})$  using  $\chi L$  by (simp add: add.commute)
then show ?case
  using  $\chi$ in L-min a $\chi$ 
  by (cases L)
    (auto simp add: build-all-simple-clss.simps[of atms-of  $\chi$ ] Let-def)
qed

lemma simplified-in-build-all:
  assumes finite  $\psi$  and distinct-mset-set  $\psi$  and  $\forall \chi \in \psi. \neg$ tautology  $\chi$ 
  shows  $\psi \subseteq \text{build-all-simple-clss (atms-of-ms } \psi)$ 
  using assms
proof (induct rule: finite.induct)
  case emptyI
  then show ?case by simp
next
  case (insertI  $\psi \chi$ ) note finite = this(1) and IH = this(2) and simp = this(3) and tauto = this(4)
  have distinct-mset  $\chi$  and  $\neg$ tautology  $\chi$ 
    using simp tauto unfolding distinct-mset-set-def by auto
  from distinct-mset-not-tautology-implies-in-build-all-simple-clss[OF this]
  have  $\chi$ :  $\chi \in \text{build-all-simple-clss (atms-of } \chi)$  .
  then have  $\psi \subseteq \text{build-all-simple-clss (atms-of-ms } \psi)$  using IH simp tauto by auto
  moreover
    have atms-of-ms  $\psi \subseteq \text{atms-of-ms (insert } \chi \psi)$  unfolding atms-of-ms-def atms-of-def by force
  ultimately
    have  $\psi \subseteq \text{build-all-simple-clss (atms-of-ms (insert } \chi \psi))$ 
      by (meson atms-of-ms-finite build-all-simple-clss-mono dual-order.trans finite.insertI local.finite)
  moreover
    have  $\chi \in \text{build-all-simple-clss (atms-of-ms (insert } \chi \psi))$ 
      using  $\chi$  finite build-all-simple-clss-mono[of atms-of-ms (insert  $\chi \psi$ )] by auto
  ultimately show ?case by auto
qed

```

11.6 Experiment: Expressing the Entailments as Locales

```

locale entail =
  fixes entail :: 'a set  $\Rightarrow$  'b  $\Rightarrow$  bool (infix  $\models_e$  50)
  assumes entail-insert[simp]:  $I \neq \{\} \implies \text{insert } L \ I \models_e x \longleftrightarrow \{L\} \models_e x \vee I \models_e x$ 
  assumes entail-union[simp]:  $I \models_e A \implies I \cup I' \models_e A$ 
begin

```

```

definition entails :: 'a set  $\Rightarrow$  'b set  $\Rightarrow$  bool (infix  $\models_{es}$  50) where
   $I \models_{es} A \longleftrightarrow (\forall a \in A. I \models_e a)$ 

```

```

lemma entails-empty[simp]:
   $I \models_{es} \{\}$ 
  unfolding entails-def by auto

```

```

lemma entails-single[iff]:
   $I \models_{es} \{a\} \longleftrightarrow I \models_e a$ 
  unfolding entails-def by auto

lemma entails-insert-l[simp]:
   $M \models_{es} A \implies \text{insert } L \ M \models_{es} A$ 
  unfolding entails-def by (metis Un-commute entail-union insert-is-Un)

lemma entails-union[iff]:  $I \models_{es} CC \cup DD \longleftrightarrow I \models_{es} CC \wedge I \models_{es} DD$ 
  unfolding entails-def by blast

lemma entails-insert[iff]:  $I \models_{es} \text{insert } C \ DD \longleftrightarrow I \models_e C \wedge I \models_{es} DD$ 
  unfolding entails-def by blast

lemma entails-insert-mono:  $DD \subseteq CC \implies I \models_{es} CC \implies I \models_{es} DD$ 
  unfolding entails-def by blast

lemma entails-union-increase[simp]:
  assumes  $I \models_{es} \psi$ 
  shows  $I \cup I' \models_{es} \psi$ 
  using assms unfolding entails-def by auto

lemma true-clss-commute-l:
   $(I \cup I' \models_{es} \psi) \longleftrightarrow (I' \cup I \models_{es} \psi)$ 
  by (simp add: Un-commute)

lemma entails-remove[simp]:  $I \models_{es} N \implies I \models_{es} \text{Set.remove } a \ N$ 
  by (simp add: entails-def)

lemma entails-remove-minus[simp]:  $I \models_{es} N \implies I \models_{es} N - A$ 
  by (simp add: entails-def)

end

interpretation true-cls: entail true-cls
  by standard (auto simp add: true-cls-def)

```

11.7 Entailment to be extended

definition true-clss-ext :: '*a* literal set \Rightarrow '*a* literal multiset set \Rightarrow bool (**infix** \models_{sext} 49)
where

$I \models_{sext} N \longleftrightarrow (\forall J. I \subseteq J \longrightarrow \text{consistent-interp } J \longrightarrow \text{total-over-m } J \ N \longrightarrow J \models_s N)$

```

lemma true-clss-imp-true-cls-ext:
   $I \models_s N \implies I \models_{sext} N$ 
  unfolding true-clss-ext-def by (metis sup.orderE true-clss-union-increase')

```

```

lemma true-clss-ext-decrease-right-remove-r:

```

```

  assumes  $I \models_{sext} N$ 
  shows  $I \models_{sext} N - \{C\}$ 
  unfolding true-clss-ext-def

```

```

proof (intro allI impI)

```

```

  fix  $J$ 

```

```

  assume

```

```

     $I \subseteq J$  and

```

```

    cons: consistent-interp  $J$  and

```

```

  tot: total-over-m  $J (N - \{C\})$ 
let ?J =  $J \cup \{Pos (atm-of P) | P. P \in \# C \wedge atm-of P \notin atm-of 'J\}$ 
have  $I \subseteq ?J$  using  $\langle I \subseteq J \rangle$  by auto
moreover have consistent-interp ?J
  using cons unfolding consistent-interp-def apply -
  apply (rule allI) by (case-tac L) (fastforce simp add: image-iff)+
moreover
  have ex-or-eq:  $\bigwedge l R J. \exists P. (l = P \vee l = -P) \wedge P \in \# C \wedge P \notin J \wedge -P \notin J$ 
     $\longleftrightarrow (l \in \# C \wedge l \notin J \wedge -l \notin J) \vee (-l \in \# C \wedge l \notin J \wedge -l \notin J)$ 
    by (metis uminus-of-uminus-id)
  have total-over-m ?J N

  using tot unfolding total-over-m-def total-over-set-def atms-of-ms-def
  apply (auto simp add: atms-of-def)
  apply (case-tac a  $a \in N - \{C\}$ )
  apply auto[]
  using atms-of-s-def atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set by fastforce+
ultimately have ?J  $\models_s N$ 
  using assms unfolding true-clss-ext-def by blast
then have ?J  $\models_s N - \{C\}$  by auto
have  $\{v \in ?J. atm-of v \in atms-of-ms (N - \{C\})\} \subseteq J$ 
  using tot unfolding total-over-m-def total-over-set-def
  by (auto intro!: rev-image-eqI)
then show  $J \models_s N - \{C\}$ 
  using true-clss-remove-unused[OF  $\langle ?J \models_s N - \{C\} \rangle$ ] unfolding true-clss-def
  by (meson true-clss-mono-set-mset-l)
qed

```

lemma consistent-true-clss-ext-satisfiable:
 assumes consistent-interp I and $I \models_{sxt} A$
 shows satisfiable A
 by (metis Un-empty-left assms satisfiable-carac subset-Un-eq sup.left-idem
 total-over-m-consistent-extension total-over-m-empty true-clss-ext-def)

lemma not-consistent-true-clss-ext:
 assumes \neg consistent-interp I
 shows $I \not\models_{sxt} A$
 by (meson assms consistent-interp-subset true-clss-ext-def)
 end

theory Prop-Resolution
imports Partial-Clausal-Logic List-More Wellfounded-More

begin

12 Resolution

12.1 Simplification Rules

inductive simplify :: ' v clauses \Rightarrow ' v clauses \Rightarrow bool **for** $N ::$ ' v clause set **where**

tautology-deletion:

$(A + \{\#Pos P\} + \{\#Neg P\}) \in N \Longrightarrow simplify\ N\ (N - \{A + \{\#Pos P\} + \{\#Neg P\}\})$

condensation:

$(A + \{\#L\} + \{\#L\}) \in N \Longrightarrow simplify\ N\ (N - \{A + \{\#L\} + \{\#L\}\} \cup \{A + \{\#L\}\})$

subsumption:

$A \in N \Longrightarrow A \subset \# B \Longrightarrow B \in N \Longrightarrow simplify\ N\ (N - \{B\})$

```

lemma simplify-preserves-un-sat':
  fixes  $N N' :: 'v \text{ clauses}$ 
  assumes simplify  $N N'$ 
  and total-over-m  $I N$ 
  shows  $I \models_s N' \longrightarrow I \models_s N$ 
  using assms
proof (induct rule: simplify.induct)
  case (tautology-deletion  $A P$ )
  then have  $I \models A + \{\#Pos\ P\} + \{\#Neg\ P\}$ 
    by (metis total-over-m-def total-over-set-literal-defined true-clss-singleton true-clss-union
      true-lit-def uminus-Neg union-commute)
  then show ?case by (metis Un-Diff-cancel2 true-clss-singleton true-clss-union)
next
  case (condensation  $A P$ )
  then show ?case by (metis Diff-insert-absorb Set.set-insert insertE true-clss-union true-clss-def
    true-clss-singleton true-clss-union)
next
  case (subsumption  $A B$ )
  have  $A \neq B$  using subsumption.hyps(2) by auto
  then have  $I \models_s N - \{B\} \Longrightarrow I \models A$  using  $\langle A \in N \rangle$  by (simp add: true-clss-def)
  moreover have  $I \models A \Longrightarrow I \models B$  using  $\langle A < \# B \rangle$  by auto
  ultimately show ?case by (metis insert-Diff-single true-clss-insert)
qed

```

```

lemma simplify-preserves-un-sat:
  fixes  $N N' :: 'v \text{ clauses}$ 
  assumes simplify  $N N'$ 
  and total-over-m  $I N$ 
  shows  $I \models_s N \longrightarrow I \models_s N'$ 
  using assms apply (induct rule: simplify.induct)
  using true-clss-def by fastforce

```

```

lemma simplify-preserves-un-sat'':
  fixes  $N N' :: 'v \text{ clauses}$ 
  assumes simplify  $N N'$ 
  and total-over-m  $I N'$ 
  shows  $I \models_s N \longrightarrow I \models_s N'$ 
  using assms apply (induct rule: simplify.induct)
  using true-clss-def by fastforce

```

```

lemma simplify-preserves-un-sat-eq:
  fixes  $N N' :: 'v \text{ clauses}$ 
  assumes simplify  $N N'$ 
  and total-over-m  $I N$ 
  shows  $I \models_s N \longleftrightarrow I \models_s N'$ 
  using simplify-preserves-un-sat simplify-preserves-un-sat' assms by blast

```

```

lemma simplify-preserves-finite:
  assumes simplify  $\psi \psi'$ 
  shows finite  $\psi \longleftrightarrow$  finite  $\psi'$ 
  using assms by (induct rule: simplify.induct, auto simp add: remove-def)

```

```

lemma rtranclp-simplify-preserves-finite:
  assumes rtranclp simplify  $\psi \psi'$ 

```

shows $\text{finite } \psi \longleftrightarrow \text{finite } \psi'$
using *assms* **by** (*induct rule: rtranclp-induct*) (*auto simp add: simplify-preserves-finite*)

lemma *simplify-atms-of-ms*:

assumes *simplify* $\psi \psi'$
shows $\text{atms-of-ms } \psi' \subseteq \text{atms-of-ms } \psi$
using *assms* **unfolding** *atms-of-ms-def*

proof (*induct rule: simplify.induct*)

case (*tautology-deletion* $A P$)

then show $?case$ **by** *auto*

next

case (*condensation* $A P$)

moreover have $A + \{\#P\# \} + \{\#P\# \} \in \psi \implies \exists x \in \psi. \text{atm-of } P \in \text{atm-of } ' \text{ set-mset } x$
by (*metis Un-iff atms-of-def atms-of-plus atms-of-singleton insert-iff*)

ultimately show $?case$ **by** (*auto simp add: atms-of-def*)

next

case (*subsumption* $A P$)

then show $?case$ **by** *auto*

qed

lemma *rtranclp-simplify-atms-of-ms*:

assumes *rtranclp simplify* $\psi \psi'$
shows $\text{atms-of-ms } \psi' \subseteq \text{atms-of-ms } \psi$
using *assms* **apply** (*induct rule: rtranclp-induct*)
apply (*fastforce intro: simplify-atms-of-ms*)
using *simplify-atms-of-ms* **by** *blast*

lemma *factoring-imp-simplify*:

assumes $\{\#L\# \} + \{\#L\# \} + C \in N$
shows $\exists N'. \text{simplify } N N'$

proof –

have $C + \{\#L\# \} + \{\#L\# \} \in N$ **using** *assms* **by** (*simp add: add.commute union-lcomm*)
from *condensation[OF this]* **show** $?thesis$ **by** *blast*

qed

12.2 Unconstrained Resolution

type-synonym $'v \text{ uncon-state} = 'v \text{ clauses}$

inductive *uncon-res* $:: 'v \text{ uncon-state} \Rightarrow 'v \text{ uncon-state} \Rightarrow \text{bool}$ **where**

resolution:

$\{\#Pos p\# \} + C \in N \implies \{\#Neg p\# \} + D \in N \implies (\{\#Pos p\# \} + C, \{\#Neg p\# \} + D) \notin \text{already-used}$

$\implies \text{uncon-res } (N) (N \cup \{C + D\}) \mid$

factoring: $\{\#L\# \} + \{\#L\# \} + C \in N \implies \text{uncon-res } N (N \cup \{C + \{\#L\# \}\})$

lemma *uncon-res-increasing*:

assumes *uncon-res* $S S'$ **and** $\psi \in S$

shows $\psi \in S'$

using *assms* **by** (*induct rule: uncon-res.induct*) *auto*

lemma *rtranclp-uncon-inference-increasing*:

assumes *rtranclp uncon-res* $S S'$ **and** $\psi \in S$

shows $\psi \in S'$

using *assms* **by** (*induct rule: rtranclp-induct*) (*auto simp add: uncon-res-increasing*)

12.2.1 Subsumption

definition *subsumes* :: 'a literal multiset \Rightarrow 'a literal multiset \Rightarrow bool **where**

subsumes χ χ' \longleftrightarrow
 $(\forall I. \text{total-over-}m\ I\ \{\chi'\} \longrightarrow \text{total-over-}m\ I\ \{\chi\})$
 $\wedge (\forall I. \text{total-over-}m\ I\ \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models \chi')$

lemma *subsumes-refl*[simp]:

subsumes χ χ
unfolding *subsumes-def* **by** *auto*

lemma *subsumes-subsumption*:

assumes *subsumes* D χ
and $C \subset\# D$ **and** $\neg \text{tautology } \chi$
shows *subsumes* C χ **unfolding** *subsumes-def*
using *assms* *subsumption-total-over-}m* *subsumption-chained* **unfolding** *subsumes-def*
by (*blast intro!*: *subset-mset.less-imp-le*)

lemma *subsumes-tautology*:

assumes *subsumes* $(C + \{\#Pos\ P\# \} + \{\#Neg\ P\# \})$ χ
shows *tautology* χ
using *assms* **unfolding** *subsumes-def* **by** (*simp add: tautology-def*)

12.3 Inference Rule

type-synonym 'v state = 'v clauses \times ('v clause \times 'v clause) set

inductive *inference-clause* :: 'v state \Rightarrow 'v clause \times ('v clause \times 'v clause) set \Rightarrow bool

(**infix** \Rightarrow_{Res} 100) **where**

resolution:

$\{\#Pos\ p\#\} + C \in N \Longrightarrow \{\#Neg\ p\#\} + D \in N \Longrightarrow (\{\#Pos\ p\#\} + C, \{\#Neg\ p\#\} + D) \notin$
already-used
 $\Longrightarrow \text{inference-clause } (N, \text{already-used}) (C + D, \text{already-used} \cup \{(\{\#Pos\ p\#\} + C, \{\#Neg\ p\#\} + D)\}) \mid$
factoring: $\{\#L\#\} + \{\#L\#\} + C \in N \Longrightarrow \text{inference-clause } (N, \text{already-used}) (C + \{\#L\#\}, \text{already-used})$

inductive *inference* :: 'v state \Rightarrow 'v state \Rightarrow bool **where**

inference-step: *inference-clause* S (*clause*, *already-used*)
 $\Longrightarrow \text{inference } S$ (*fst* $S \cup \{\text{clause}\}$, *already-used*)

abbreviation *already-used-inv*

:: 'a literal multiset set \times ('a literal multiset \times 'a literal multiset) set \Rightarrow bool **where**

already-used-inv state \equiv

$(\forall (A, B) \in \text{snd state}. \exists p. \text{Pos } p \in\# A \wedge \text{Neg } p \in\# B \wedge$
 $((\exists \chi \in \text{fst state}. \text{subsumes } \chi ((A - \{\#Pos\ p\#\}) + (B - \{\#Neg\ p\#\})))$
 $\vee \text{tautology } ((A - \{\#Pos\ p\#\}) + (B - \{\#Neg\ p\#\}))))$

lemma *inference-clause-preserves-already-used-inv*:

assumes *inference-clause* S S'
and *already-used-inv* S
shows *already-used-inv* (*fst* $S \cup \{\text{fst } S'\}$, *snd* S')
using *assms* **apply** (*induct rule: inference-clause.induct*)
by *fastforce+*

lemma *inference-preserves-already-used-inv*:

```

assumes inference  $S S'$ 
and already-used-inv  $S$ 
shows already-used-inv  $S'$ 
using assms
proof (induct rule: inference.induct)
  case (inference-step  $S$  clause already-used)
  then show ?case
    using inference-clause-preserves-already-used-inv[of  $S$  (clause, already-used)] by simp
qed

lemma rtranclp-inference-preserves-already-used-inv:
  assumes rtranclp inference  $S S'$ 
  and already-used-inv  $S$ 
  shows already-used-inv  $S'$ 
  using assms apply (induct rule: rtranclp-induct, simp)
  using inference-preserves-already-used-inv unfolding tautology-def by fast

lemma subsumes-condensation:
  assumes subsumes  $(C + \{\#L\# \} + \{\#L\# \}) D$ 
  shows subsumes  $(C + \{\#L\# \}) D$ 
  using assms unfolding subsumes-def by simp

lemma simplify-preserves-already-used-inv:
  assumes simplify  $N N'$ 
  and already-used-inv  $(N, \text{already-used})$ 
  shows already-used-inv  $(N', \text{already-used})$ 
  using assms
proof (induct rule: simplify.induct)
  case (condensation  $C L$ )
  then show ?case
    using subsumes-condensation by simp fast
next
  {
    fix  $a :: 'a$  and  $A :: 'a$  set and  $P$ 
    have  $(\exists x \in \text{Set.remove } a A. P x) \longleftrightarrow (\exists x \in A. x \neq a \wedge P x)$  by auto
  } note ex-member-remove = this
  {
    fix  $a a0 :: 'v$  clause and  $A :: 'v$  clauses and  $y$ 
    assume  $a \in A$  and  $a0 \subset\# a$ 
    then have  $(\exists x \in A. \text{subsumes } x y) \longleftrightarrow (\text{subsumes } a y \vee (\exists x \in A. x \neq a \wedge \text{subsumes } x y))$ 
    by auto
  } note tt2 = this
case (subsumption  $A B$ ) note  $A = \text{this}(1)$  and  $AB = \text{this}(2)$  and  $B = \text{this}(3)$  and  $\text{inv} = \text{this}(4)$ 
show ?case
proof (standard, standard)
  fix  $x a b$ 
  assume  $x: x \in \text{snd } (N - \{B\}, \text{already-used})$  and [simp]:  $x = (a, b)$ 
  obtain  $p$  where  $p: \text{Pos } p \in\# a \wedge \text{Neg } p \in\# b$  and
     $q: (\exists \chi \in N. \text{subsumes } \chi (a - \{\#\text{Pos } p\# \} + (b - \{\#\text{Neg } p\# \})))$ 
     $\vee \text{tautology } (a - \{\#\text{Pos } p\# \} + (b - \{\#\text{Neg } p\# \}))$ 
  using  $\text{inv } x$  by fastforce
  consider (taut)  $\text{tautology } (a - \{\#\text{Pos } p\# \} + (b - \{\#\text{Neg } p\# \})) \mid$ 
     $(\chi) \chi$  where  $\chi \in N$   $\text{subsumes } \chi (a - \{\#\text{Pos } p\# \} + (b - \{\#\text{Neg } p\# \}))$ 
     $\neg \text{tautology } (a - \{\#\text{Pos } p\# \} + (b - \{\#\text{Neg } p\# \}))$ 
  using  $q$  by auto

```



```

then show
   $\exists p. \text{Pos } p \in \# a \wedge \text{Neg } p \in \# b$ 
   $\wedge ((\exists \chi \in \text{fst } (N - \{B\}, \text{already-used}). \text{subsumes } \chi (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\}))))$ 
   $\vee \text{tautology } (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
proof cases
  case taut
    then show ?thesis using p by auto
  next
    case  $\chi$  note  $H = \text{this}$ 
    show ?thesis using p A AB B subsumes-subsumption[OF - AB H(3)] H(1,2) by auto
  qed
qed
next
case (tautology-deletion C P)
then show ?case apply clarify
proof –
  fix a b
  assume  $C + \{\# \text{Pos } P\} + \{\# \text{Neg } P\} \in N$ 
  assume already-used-inv (N, already-used)
  and (a, b)  $\in \text{snd } (N - \{C + \{\# \text{Pos } P\} + \{\# \text{Neg } P\}\}, \text{already-used})$ 
  then obtain p where
     $\text{Pos } p \in \# a \wedge \text{Neg } p \in \# b \wedge$ 
     $((\exists \chi \in \text{fst } (N \cup \{C + \{\# \text{Pos } P\} + \{\# \text{Neg } P\}\}, \text{already-used}).$ 
       $\text{subsumes } \chi (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
       $\vee \text{tautology } (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
    by fastforce
  moreover have tautology (C + {#Pos P} + {#Neg P}) by auto
  ultimately show
     $\exists p. \text{Pos } p \in \# a \wedge \text{Neg } p \in \# b$ 
     $\wedge ((\exists \chi \in \text{fst } (N - \{C + \{\# \text{Pos } P\} + \{\# \text{Neg } P\}\}, \text{already-used}).$ 
       $\text{subsumes } \chi (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
       $\vee \text{tautology } (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
    by (metis (no-types) Diff-iff Un-insert-right empty-iff fst-conv insertE subsumes-tautology
      sup-bot.right-neutral)
  qed
qed

```

lemma

factoring-satisfiable: $I \models \{\#L\} + \{\#L\} + C \longleftrightarrow I \models \{\#L\} + C$ **and**

resolution-satisfiable:

consistent-interp $I \implies I \models \{\# \text{Pos } p\} + C \implies I \models \{\# \text{Neg } p\} + D \implies I \models C + D$ **and**

factoring-same-vars: $\text{atms-of } (\{\#L\} + \{\#L\} + C) = \text{atms-of } (\{\#L\} + C)$

unfolding true-cls-def consistent-interp-def **by** (fastforce split: split-if-asm)+

lemma inference-increasing:

assumes inference S S' **and** $\psi \in \text{fst } S$

shows $\psi \in \text{fst } S'$

using assms **by** (induct rule: inference.induct, auto)

lemma rtranclp-inference-increasing:

assumes rtranclp inference S S' **and** $\psi \in \text{fst } S$

shows $\psi \in \text{fst } S'$

using assms **by** (induct rule: rtranclp-induct, auto simp add: inference-increasing)

lemma *inference-clause-already-used-increasing*:
assumes *inference-clause* $S S'$
shows $\text{snd } S \subseteq \text{snd } S'$
using *assms* **by** (*induct rule:inference-clause.induct*, *auto*)

lemma *inference-already-used-increasing*:
assumes *inference* $S S'$
shows $\text{snd } S \subseteq \text{snd } S'$
using *assms* **apply** (*induct rule:inference.induct*)
using *inference-clause-already-used-increasing* **by** *fastforce*

lemma *inference-clause-preserves-un-sat*:
fixes $N N' :: 'v \text{ clauses}$
assumes *inference-clause* $T T'$
and *total-over-m* $I (\text{fst } T)$
and *consistent: consistent-interp* I
shows $I \models_s \text{fst } T \longleftrightarrow I \models_s \text{fst } T \cup \{\text{fst } T'\}$
using *assms* **apply** (*induct rule: inference-clause.induct*)
unfolding *consistent-interp-def true-clss-def* **by** *auto force+*

lemma *inference-preserves-un-sat*:
fixes $N N' :: 'v \text{ clauses}$
assumes *inference* $T T'$
and *total-over-m* $I (\text{fst } T)$
and *consistent: consistent-interp* I
shows $I \models_s \text{fst } T \longleftrightarrow I \models_s \text{fst } T'$
using *assms* **apply** (*induct rule: inference.induct*)
using *inference-clause-preserves-un-sat* **by** *fastforce*

lemma *inference-clause-preserves-atms-of-ms*:
assumes *inference-clause* $S S'$
shows *atms-of-ms* $(\text{fst } (\text{fst } S \cup \{\text{fst } S'\}, \text{snd } S')) \subseteq \text{atms-of-ms } (\text{fst } S)$
using *assms* **apply** (*induct rule: inference-clause.induct*)
apply *auto*
apply (*metis Set.set-insert UnCI atms-of-ms-insert atms-of-plus*)
apply (*metis Set.set-insert UnCI atms-of-ms-insert atms-of-plus*)
apply (*simp add: in-m-in-literals union-assoc*)
unfolding *atms-of-ms-def* **using** *assms* **by** *fastforce*

lemma *inference-preserves-atms-of-ms*:
fixes $N N' :: 'v \text{ clauses}$
assumes *inference* $T T'$
shows *atms-of-ms* $(\text{fst } T') \subseteq \text{atms-of-ms } (\text{fst } T)$
using *assms* **apply** (*induct rule: inference.induct*)
using *inference-clause-preserves-atms-of-ms* **by** *fastforce*

lemma *inference-preserves-total*:
fixes $N N' :: 'v \text{ clauses}$
assumes *inference* $(N, \text{already-used}) (N', \text{already-used}')$
shows *total-over-m* $I N \implies \text{total-over-m } I N'$
using *assms* *inference-preserves-atms-of-ms* **unfolding** *total-over-m-def total-over-set-def*
by *fastforce*

lemma *rtranclp-inference-preserves-total*:
assumes *rtranclp inference T T'*
shows *total-over-m I (fst T) \implies total-over-m I (fst T')*
using *assms* **by** (*induct rule: rtranclp-induct, auto simp add: inference-preserves-total*)

lemma *rtranclp-inference-preserves-un-sat*:
assumes *rtranclp inference N N'*
and *total-over-m I (fst N)*
and *consistent: consistent-interp I*
shows *I \models_s fst N \longleftrightarrow I \models_s fst N'*
using *assms* **apply** (*induct rule: rtranclp-induct*)
apply (*simp add: inference-preserves-un-sat*)
using *inference-preserves-un-sat rtranclp-inference-preserves-total* **by** *blast*

lemma *inference-preserves-finite*:
assumes *inference ψ ψ' and finite (fst ψ)*
shows *finite (fst ψ')*
using *assms* **by** (*induct rule: inference.induct, auto simp add: simplify-preserves-finite*)

lemma *inference-clause-preserves-finite-snd*:
assumes *inference-clause ψ ψ' and finite (snd ψ)*
shows *finite (snd ψ')*
using *assms* **by** (*induct rule: inference-clause.induct, auto*)

lemma *inference-preserves-finite-snd*:
assumes *inference ψ ψ' and finite (snd ψ)*
shows *finite (snd ψ')*
using *assms inference-clause-preserves-finite-snd* **by** (*induct rule: inference.induct, fastforce*)

lemma *rtranclp-inference-preserves-finite*:
assumes *rtranclp inference ψ ψ' and finite (fst ψ)*
shows *finite (fst ψ')*
using *assms* **by** (*induct rule: rtranclp-induct*)
(auto simp add: simplify-preserves-finite inference-preserves-finite)

lemma *consistent-interp-insert*:
assumes *consistent-interp I*
and *atm-of P \notin atm-of 'I*
shows *consistent-interp (insert P I)*
proof –
have *P: insert P I = I \cup {P}* **by** *auto*
show *?thesis* **unfolding** *P*
apply (*rule consistent-interp-disjoint*)
using *assms* **by** (*auto simp add: atms-of-s-def*)
qed

lemma *simplify-clause-preserves-sat*:
assumes *simp: simplify ψ ψ'*
and *satisfiable ψ'*
shows *satisfiable ψ*
using *assms*

proof *induction*

case (*tautology-deletion* $A\ P$) **note** $AP = \text{this}(1)$ **and** $\text{sat} = \text{this}(2)$
let $?A' = A + \{\#Pos\ P\# \} + \{\#Neg\ P\# \}$
let $? \psi' = \psi - \{?A'\}$
obtain I **where**
 $I: I \models_s ? \psi'$ **and**
 $\text{cons}: \text{consistent-interp}\ I$ **and**
 $\text{tot}: \text{total-over-m}\ I\ ? \psi'$
using sat **unfolding** *satisfiable-def* **by** *auto*
{ assume $Pos\ P \in I \vee Neg\ P \in I$
then have $I \models ?A'$ **by** *auto*
then have $I \models_s \psi$ **using** I **by** (*metis insert-Diff tautology-deletion.hyps true-clss-insert*)
then have $?case$ **using** cons tot **by** *auto*
}
moreover {
assume $Pos: Pos\ P \notin I$ **and** $Neg: Neg\ P \notin I$
then have *consistent-interp* $(I \cup \{Pos\ P\})$ **using** cons **by** *simp*
moreover have $I'A: I \cup \{Pos\ P\} \models ?A'$ **by** *auto*
have $\{Pos\ P\} \cup I \models_s \psi - \{A + \{\#Pos\ P\# \} + \{\#Neg\ P\# \}\}$
using $\langle I \models_s \psi - \{A + \{\#Pos\ P\# \} + \{\#Neg\ P\# \}\rangle$ *true-clss-union-increase'* **by** *blast*
then have $I \cup \{Pos\ P\} \models_s \psi$
by (*metis (no-types) Un-empty-right Un-insert-left Un-insert-right I'A insert-Diff*
sup-bot.left-neutral tautology-deletion.hyps true-clss-insert)
ultimately have $?case$ **using** *satisfiable-carac'* **by** *blast*
}
ultimately show $?case$ **by** *blast*

next

case (*condensation* $A\ L$) **note** $AL = \text{this}(1)$ **and** $\text{sat} = \text{this}(2)$
have $f3: \text{simplify}\ \psi\ (\psi - \{A + \{\#L\# \} + \{\#L\# \}\} \cup \{A + \{\#L\# \}\})$
using AL *simplify.condensation* **by** *blast*
obtain $LL :: 'a\ \text{literal multiset set} \Rightarrow 'a\ \text{literal set}$ **where**
 $f4: LL\ (\psi - \{A + \{\#L\# \} + \{\#L\# \}\} \cup \{A + \{\#L\# \}\}) \models_s \psi - \{A + \{\#L\# \} + \{\#L\# \}\} \cup \{A + \{\#L\# \}\}$
 $\wedge \text{consistent-interp}\ (LL\ (\psi - \{A + \{\#L\# \} + \{\#L\# \}\} \cup \{A + \{\#L\# \}\}))$
 $\wedge \text{total-over-m}\ (LL\ (\psi - \{A + \{\#L\# \} + \{\#L\# \}\} \cup \{A + \{\#L\# \}\}))\ (\psi - \{A + \{\#L\# \} + \{\#L\# \}\} \cup \{A + \{\#L\# \}\})$
using sat **by** (*meson satisfiable-def*)
have $f5: \text{insert}\ (A + \{\#L\# \} + \{\#L\# \})\ (\psi - \{A + \{\#L\# \} + \{\#L\# \}\}) = \psi$
using AL **by** *fastforce*
have $\text{atms-of}\ (A + \{\#L\# \} + \{\#L\# \}) = \text{atms-of}\ (\{\#L\# \} + A)$
by *simp*
then show $?case$
using $f5\ f4\ f3$ **by** (*metis (no-types) add commute satisfiable-def simplify-preserved-un-sat'*
total-over-m-insert total-over-m-union)

next

case (*subsumption* $A\ B$) **note** $A = \text{this}(1)$ **and** $AB = \text{this}(2)$ **and** $B = \text{this}(3)$ **and** $\text{sat} = \text{this}(4)$
let $? \psi' = \psi - \{B\}$
obtain I **where** $I: I \models_s ? \psi'$ **and** $\text{cons}: \text{consistent-interp}\ I$ **and** $\text{tot}: \text{total-over-m}\ I\ ? \psi'$
using sat **unfolding** *satisfiable-def* **by** *auto*
have $I \models A$ **using** $A\ I$ **by** (*metis AB Diff-iff subset-mset.less-irrefl singletonD true-clss-def*)
then have $I \models B$ **using** AB *subset-mset.less-imp-le true-clss-mono-leD* **by** *blast*
then have $I \models_s \psi$ **using** I **by** (*metis insert-Diff-single true-clss-insert*)
then show $?case$ **using** cons *satisfiable-carac'* **by** *blast*

qed

```

lemma simplify-preserves-unsat:
  assumes inference  $\psi$   $\psi'$ 
  shows satisfiable (fst  $\psi'$ )  $\longrightarrow$  satisfiable (fst  $\psi$ )
  using assms apply (induct rule: inference.induct)
  using satisfiable-decreasing by (metis fst-conv)+

lemma inference-preserves-unsat:
  assumes inference**  $S$   $S'$ 
  shows satisfiable (fst  $S'$ )  $\longrightarrow$  satisfiable (fst  $S$ )
  using assms apply (induct rule: rtranclp-induct)
  apply simp-all
  using simplify-preserves-unsat by blast

datatype 'v sem-tree = Node 'v 'v sem-tree 'v sem-tree | Leaf

fun sem-tree-size :: 'v sem-tree  $\Rightarrow$  nat where
  sem-tree-size Leaf = 0 |
  sem-tree-size (Node - ag ad) = 1 + sem-tree-size ag + sem-tree-size ad

lemma sem-tree-size[case-names bigger]:
  ( $\bigwedge xs:: 'v$  sem-tree. ( $\bigwedge ys:: 'v$  sem-tree. sem-tree-size ys < sem-tree-size xs  $\Longrightarrow$  P ys)  $\Longrightarrow$  P xs)
   $\Longrightarrow$  P xs
  by (fact Nat.measure-induct-rule)

fun partial-interps :: 'v sem-tree  $\Rightarrow$  'v interp  $\Rightarrow$  'v clauses  $\Rightarrow$  bool where
  partial-interps Leaf  $I$   $\psi$  = ( $\exists \chi. \neg I \models \chi \wedge \chi \in \psi \wedge \text{total-over-}m\ I\ \{\chi\}$ ) |
  partial-interps (Node v ag ad)  $I$   $\psi \longleftrightarrow$ 
    (partial-interps ag ( $I \cup \{\text{Pos } v\}$ )  $\psi \wedge$  partial-interps ad ( $I \cup \{\text{Neg } v\}$ )  $\psi$ )

lemma simplify-preserve-partial-leaf:
  simplify  $N\ N' \Longrightarrow$  partial-interps Leaf  $I\ N \Longrightarrow$  partial-interps Leaf  $I\ N'$ 
  apply (induct rule: simplify.induct)
  using union-lcomm apply auto[1]
  apply (simp, metis atms-of-plus total-over-set-union true-cls-union)
  apply simp
  by (metis atms-of-ms-singleton mset-le-exists-conv subset-mset-def true-cls-mono-leD
    total-over-m-def total-over-m-sum)

lemma simplify-preserve-partial-tree:
  assumes simplify  $N\ N'$ 
  and partial-interps  $t\ I\ N$ 
  shows partial-interps  $t\ I\ N'$ 
  using assms apply (induct  $t$  arbitrary:  $I$ , simp)
  using simplify-preserve-partial-leaf by metis

lemma inference-preserve-partial-tree:
  assumes inference  $S\ S'$ 
  and partial-interps  $t\ I$  (fst  $S$ )
  shows partial-interps  $t\ I$  (fst  $S'$ )
  using assms apply (induct  $t$  arbitrary:  $I$ , simp-all)
  by (meson inference-increasing)

```

```

lemma rtranclp-inference-preserve-partial-tree:
  assumes rtranclp inference N N'
  and partial-interps t I (fst N)
  shows partial-interps t I (fst N')
  using assms apply (induct rule: rtranclp-induct, auto)
  using inference-preserve-partial-tree by force

function build-sem-tree :: 'v :: linorder set  $\Rightarrow$  'v clauses  $\Rightarrow$  'v sem-tree where
build-sem-tree atms  $\psi$  =
  (if atms = {}  $\vee \neg$  finite atms
   then Leaf
   else Node (Min atms) (build-sem-tree (Set.remove (Min atms) atms)  $\psi$ )
    (build-sem-tree (Set.remove (Min atms) atms)  $\psi$ ))
by auto
termination
  apply (relation measure ( $\lambda(A, -). \text{card } A$ ), simp-all)
  apply (metis Min-in card-Diff1-less remove-def)+
done
declare build-sem-tree.induct[case-names tree]

lemma unsatisfiable-empty[simp]:
   $\neg$ unsatisfiable {}
  unfolding satisfiable-def apply auto
  using consistent-interp-def unfolding total-over-m-def total-over-set-def atms-of-ms-def by blast

lemma partial-interps-build-sem-tree-atms-general:
  fixes  $\psi :: 'v :: \text{linorder clauses}$  and  $p :: 'v \text{ literal list}$ 
  assumes unsat: unsatisfiable  $\psi$  and finite  $\psi$  and consistent-interp I
  and finite atms
  and atms-of-ms  $\psi$  = atms  $\cup$  atms-of-s I and atms  $\cap$  atms-of-s I = {}
  shows partial-interps (build-sem-tree atms  $\psi$ ) I  $\psi$ 
  using assms
proof (induct arbitrary: I rule: build-sem-tree.induct)
case (1 atms  $\psi$  Ia) note IH1 = this(1) and IH2 = this(2) and unsat = this(3) and finite = this(4)
  and cons = this(5) and f = this(6) and un = this(7) and disj = this(8)
  {
    assume atms: atms = {}
    then have atmsIa: atms-of-ms  $\psi$  = atms-of-s Ia using un by auto
    then have total-over-m Ia  $\psi$  unfolding total-over-m-def atmsIa by auto
    then have  $\chi: \exists \chi \in \psi. \neg Ia \models \chi$ 
      using unsat cons unfolding true-clss-def satisfiable-def by auto
    then have build-sem-tree atms  $\psi$  = Leaf using atms by auto
    moreover
      have tot:  $\bigwedge \chi. \chi \in \psi \implies \text{total-over-m Ia } \{\chi\}$ 
      unfolding total-over-m-def total-over-set-def atms-of-ms-def atms-of-s-def
      using atmsIa atms-of-ms-def by fastforce
    have partial-interps Leaf Ia  $\psi$ 
      using  $\chi$  tot by (auto simp add: total-over-m-def total-over-set-def atms-of-ms-def)

    ultimately have ?case by metis
  }
moreover {

```

```

assume atms: atms ≠ {}
have build-sem-tree atms  $\psi = \text{Node } (\text{Min } \textit{atms}) (\text{build-sem-tree } (\text{Set.remove } (\text{Min } \textit{atms}) \textit{atms}) \psi)$ 
  (build-sem-tree (Set.remove (Min atms) atms)  $\psi$ )
using build-sem-tree.simps[of atms  $\psi$ ] f atms by metis

have consistent-interp (Ia  $\cup \{\text{Pos } (\text{Min } \textit{atms})\}$ ) unfolding consistent-interp-def
  by (metis Int-iff Min-in Un-iff atm-of-uminus atms cons consistent-interp-def disj empty-iff
    f in-atms-of-s-decomp insert-iff literal.distinct(1) literal.exhaust-sel literal.sel(2)
    uminus-Neg uminus-Pos)
moreover have atms-of-ms  $\psi = \text{Set.remove } (\text{Min } \textit{atms}) \textit{atms} \cup \textit{atms-of-s } (\text{Ia} \cup \{\text{Pos } (\text{Min } \textit{atms})\})$ 
  using Min-in atms f un by fastforce
moreover have disj': Set.remove (Min atms) atms  $\cap \textit{atms-of-s } (\text{Ia} \cup \{\text{Pos } (\text{Min } \textit{atms})\}) = \{\}$ 
  by simp (metis disj disjoint-iff-not-equal member-remove)
moreover have finite (Set.remove (Min atms) atms) using f by (simp add: remove-def)
ultimately have subtree1: partial-interps (build-sem-tree (Set.remove (Min atms) atms)  $\psi$ )
  (Ia  $\cup \{\text{Pos } (\text{Min } \textit{atms})\}$ )  $\psi$ 
using IH1[of Ia  $\cup \{\text{Pos } (\text{Min } (\textit{atms}))\}$ ] atms f unsat finite by metis

have consistent-interp (Ia  $\cup \{\text{Neg } (\text{Min } \textit{atms})\}$ ) unfolding consistent-interp-def
  by (metis Int-iff Min-in Un-iff atm-of-uminus atms cons consistent-interp-def disj empty-iff
    f in-atms-of-s-decomp insert-iff literal.distinct(1) literal.exhaust-sel literal.sel(2)
    uminus-Neg)
moreover have atms-of-ms  $\psi = \text{Set.remove } (\text{Min } \textit{atms}) \textit{atms} \cup \textit{atms-of-s } (\text{Ia} \cup \{\text{Neg } (\text{Min } \textit{atms})\})$ 
  using (atms-of-ms  $\psi = \text{Set.remove } (\text{Min } \textit{atms}) \textit{atms} \cup \textit{atms-of-s } (\text{Ia} \cup \{\text{Pos } (\text{Min } \textit{atms})\})$ ) by
blast

moreover have disj': Set.remove (Min atms) atms  $\cap \textit{atms-of-s } (\text{Ia} \cup \{\text{Neg } (\text{Min } \textit{atms})\}) = \{\}$ 
  using disj by auto
moreover have finite (Set.remove (Min atms) atms) using f by (simp add: remove-def)
ultimately have subtree2: partial-interps (build-sem-tree (Set.remove (Min atms) atms)  $\psi$ )
  (Ia  $\cup \{\text{Neg } (\text{Min } \textit{atms})\}$ )  $\psi$ 
using IH2[of Ia  $\cup \{\text{Neg } (\text{Min } (\textit{atms}))\}$ ] atms f unsat finite by metis

then have ?case
  using IH1 subtree1 subtree2 f local.finite unsat atms by simp
}
ultimately show ?case by metis
qed

```

```

lemma partial-interps-build-sem-tree-atms:
  fixes  $\psi :: 'v :: \text{linorder clauses}$  and  $p :: 'v \text{ literal list}$ 
  assumes unsat: unsatisfiable  $\psi$  and finite: finite  $\psi$ 
  shows partial-interps (build-sem-tree (atms-of-ms  $\psi$ )  $\psi$ )  $\{\}$   $\psi$ 
proof –
  have consistent-interp  $\{\}$  unfolding consistent-interp-def by auto
  moreover have atms-of-ms  $\psi = \textit{atms-of-ms } \psi \cup \textit{atms-of-s } \{\}$  unfolding atms-of-s-def by auto
  moreover have atms-of-ms  $\psi \cap \textit{atms-of-s } \{\} = \{\}$  unfolding atms-of-s-def by auto
  moreover have finite (atms-of-ms  $\psi$ ) unfolding atms-of-ms-def using finite by simp
  ultimately show partial-interps (build-sem-tree (atms-of-ms  $\psi$ )  $\psi$ )  $\{\}$   $\psi$ 
    using partial-interps-build-sem-tree-atms-general[of  $\psi \{\}$  atms-of-ms  $\psi$ ] assms by metis
qed

```

```

lemma can-decrease-count:
  fixes  $\psi'' :: 'v \text{ clauses} \times ('v \text{ clause} \times 'v \text{ clause} \times 'v) \text{ set}$ 

```

```

assumes count  $\chi$   $L = n$ 
and  $L \in \# \chi$  and  $\chi \in \text{fst } \psi$ 
shows  $\exists \psi' \chi'. \text{inference}^{**} \psi \psi' \wedge \chi' \in \text{fst } \psi' \wedge (\forall L. L \in \# \chi \longleftrightarrow L \in \# \chi')$ 
 $\wedge \text{count } \chi' L = 1$ 
 $\wedge (\forall \varphi. \varphi \in \text{fst } \psi \longrightarrow \varphi \in \text{fst } \psi')$ 
 $\wedge (I \models \chi \longleftrightarrow I \models \chi')$ 
 $\wedge (\forall I'. \text{total-over-m } I' \{\chi\} \longrightarrow \text{total-over-m } I' \{\chi'\})$ 

using assms
proof (induct  $n$  arbitrary:  $\chi \psi$ )
  case 0
  then show ?case by simp
next
  case (Suc  $n \chi$ )
  note  $IH = \text{this}(1)$  and  $\text{count} = \text{this}(2)$  and  $L = \text{this}(3)$  and  $\chi = \text{this}(4)$ 
  {
    assume  $n = 0$ 
    then have inference**  $\psi \psi$ 
    and  $\chi \in \text{fst } \psi$ 
    and  $\forall L. (L \in \# \chi) \longleftrightarrow (L \in \# \chi)$ 
    and  $\text{count } \chi L = (1::\text{nat})$ 
    and  $\forall \varphi. \varphi \in \text{fst } \psi \longrightarrow \varphi \in \text{fst } \psi$ 
    by (auto simp add: count L  $\chi$ )
    then have ?case by metis
  }
  moreover {
    assume  $n > 0$ 
    then have  $\exists C. \chi = C + \{\#L, L\# \}$ 
    by (metis L One-nat-def add-diff-cancel-right' count-diff count-single diff-Suc-Suc diff-zero
      local.count multi-member-split union-assoc)
    then obtain  $C$  where  $C: \chi = C + \{\#L, L\# \}$  by metis
    let  $? \chi' = C + \{\#L\# \}$ 
    let  $? \psi' = (\text{fst } \psi \cup \{? \chi'\}, \text{snd } \psi)$ 
    have  $\varphi: \forall \varphi \in \text{fst } \psi. (\varphi \in \text{fst } \psi \vee \varphi \neq ? \chi') \longleftrightarrow \varphi \in \text{fst } ? \psi'$  unfolding  $C$  by auto
    have inf: inference  $\psi ? \psi'$ 
    using  $C$  factoring  $\chi$  prod.collapse union-commute inference-step by metis
    moreover have  $\text{count}' : \text{count } ? \chi' L = n$  using  $C$  count by auto
    moreover have  $L \chi' : L : \# ? \chi'$  by auto
    moreover have  $\chi' \psi' : ? \chi' \in \text{fst } ? \psi'$  by auto
    ultimately obtain  $\psi''$  and  $\chi''$ 
    where
    inference**  $? \psi' \psi''$  and
     $\alpha: \chi'' \in \text{fst } \psi''$  and
     $\forall La. (La \in \# ? \chi') \longleftrightarrow (La \in \# \chi'')$  and
     $\beta: \text{count } \chi'' L = (1::\text{nat})$  and
     $\varphi': \forall \varphi. \varphi \in \text{fst } ? \psi' \longrightarrow \varphi \in \text{fst } \psi''$  and
     $I \chi: I \models ? \chi' \longleftrightarrow I \models \chi''$  and
     $\text{tot}: \forall I'. \text{total-over-m } I' \{? \chi'\} \longrightarrow \text{total-over-m } I' \{\chi''\}$ 
    using  $IH[\text{of } ? \chi' ? \psi']$  count'  $L \chi' \chi' \psi'$  by blast

    then have inference**  $\psi \psi''$ 
    and  $\forall La. (La \in \# \chi) \longleftrightarrow (La \in \# \chi'')$ 
    using inf unfolding  $C$  by auto
    moreover have  $\forall \varphi. \varphi \in \text{fst } \psi \longrightarrow \varphi \in \text{fst } \psi''$  using  $\varphi \varphi'$  by metis
    moreover have  $I \models \chi \longleftrightarrow I \models \chi''$  using  $I \chi$  unfolding true-cls-def  $C$  by auto
    moreover have  $\forall I'. \text{total-over-m } I' \{\chi\} \longrightarrow \text{total-over-m } I' \{\chi''\}$ 
  }

```



```

    using tot unfolding C total-over-m-def by auto
    ultimately have ?case using  $\varphi \varphi' \alpha \beta$  by metis
  }
  ultimately show ?case by auto
qed

lemma can-decrease-tree-size:
  fixes  $\psi :: 'v$  state and tree ::  $'v$  sem-tree
  assumes finite (fst  $\psi$ ) and already-used-inv  $\psi$ 
  and partial-interps tree I (fst  $\psi$ )
  shows  $\exists (tree' :: 'v$  sem-tree)  $\psi'. inference^{**} \psi \psi' \wedge partial-interps tree' I (fst \psi')$ 
     $\wedge (sem-tree-size tree' < sem-tree-size tree \vee sem-tree-size tree = 0)$ 
  using assms
proof (induct arbitrary: I rule: sem-tree-size)
  case (bigger xs I) note IH = this(1) and finite = this(2) and a-u-i = this(3) and part = this(4)

  {
    assume sem-tree-size xs = 0
    then have ?case using part by blast
  }

  moreover {
    assume sn0: sem-tree-size xs > 0
    obtain ag ad v where xs: xs = Node v ag ad using sn0 by (case-tac xs, auto)
    {
      assume sem-tree-size ag = 0 and sem-tree-size ad = 0
      then have ag: ag = Leaf and ad: ad = Leaf by (case-tac ag, auto) (case-tac ad, auto)

      then obtain  $\chi \chi'$  where
         $\chi: \neg I \cup \{Pos\ v\} \models \chi$  and
        tot $\chi$ : total-over-m (I  $\cup \{Pos\ v\}$ ) { $\chi$ } and
         $\chi\psi$ :  $\chi \in fst\ \psi$  and
         $\chi': \neg I \cup \{Neg\ v\} \models \chi'$  and
        tot $\chi'$ : total-over-m (I  $\cup \{Neg\ v\}$ ) { $\chi'$ } and
         $\chi'\psi$ :  $\chi' \in fst\ \psi$ 
        using part unfolding xs by auto
      have Posv:  $\neg Pos\ v \in \# \chi$  using  $\chi$  unfolding true-cls-def true-lit-def by auto
      have Negv:  $\neg Neg\ v \in \# \chi'$  using  $\chi'$  unfolding true-cls-def true-lit-def by auto
      {
        assume Neg $\chi$ :  $\neg Neg\ v \in \# \chi$ 
        have  $\neg I \models \chi$  using  $\chi$  Posv unfolding true-cls-def true-lit-def by auto
        moreover have total-over-m I { $\chi$ }
          using Posv Neg $\chi$  atm-imp-pos-or-neg-lit tot $\chi$  unfolding total-over-m-def total-over-set-def
          by fastforce
        ultimately have partial-interps Leaf I (fst  $\psi$ )
          and sem-tree-size Leaf < sem-tree-size xs
          and inference $^{**} \psi \psi$ 
          unfolding xs by (auto simp add:  $\chi\psi$ )
      }
      moreover {
        assume Pos $\chi$ :  $\neg Pos\ v \in \# \chi'$ 
        then have I $\chi$ :  $\neg I \models \chi'$  using  $\chi'$  Posv unfolding true-cls-def true-lit-def by auto
        moreover have total-over-m I { $\chi'$ }
          using Negv Pos $\chi$  atm-imp-pos-or-neg-lit tot $\chi'$ 
          unfolding total-over-m-def total-over-set-def by fastforce
      }
    }
  }

```

```

ultimately have partial-interps Leaf I (fst  $\psi$ ) and
  sem-tree-size Leaf < sem-tree-size xs and
  inference**  $\psi$   $\psi$ 
  using  $\chi' \psi$   $I_\chi$  unfolding xs by auto
}
moreover {
  assume neg: Neg v  $\in \# \chi$  and pos: Pos v  $\in \# \chi'$ 
  then obtain  $\psi' \chi^2$  where inf: rtrancplp inference  $\psi \psi'$  and  $\chi^2 \text{incl}$ :  $\chi^2 \in \text{fst } \psi'$ 
    and  $\chi \chi^2 \text{-incl}$ :  $\forall L. L : \# \chi \longleftrightarrow L : \# \chi^2$ 
    and count $\chi^2$ : count  $\chi^2$  (Neg v) = 1
    and  $\varphi$ :  $\forall \varphi :: 'v$  literal multiset.  $\varphi \in \text{fst } \psi \longrightarrow \varphi \in \text{fst } \psi'$ 
    and  $I_\chi$ :  $I \models \chi \longleftrightarrow I \models \chi^2$ 
    and tot-imp $\chi$ :  $\forall I'. \text{total-over-m } I' \{ \chi \} \longrightarrow \text{total-over-m } I' \{ \chi^2 \}$ 
    using can-decrease-count[of  $\chi$  Neg v count  $\chi$  (Neg v)  $\psi$  I]  $\chi \psi \chi' \psi$  by auto

  have  $\chi' \in \text{fst } \psi'$  by (simp add:  $\chi' \psi \varphi$ )
  with pos
  obtain  $\psi'' \chi^{2'}$  where
    inf': inference**  $\psi' \psi''$ 
    and  $\chi^{2'} \text{-incl}$ :  $\chi^{2'} \in \text{fst } \psi''$ 
    and  $\chi' \chi^{2'} \text{-incl}$ :  $\forall L :: 'v$  literal.  $(L \in \# \chi') = (L \in \# \chi^{2'})$ 
    and count $\chi^{2'}$ : count  $\chi^{2'}$  (Pos v) = (1::nat)
    and  $\varphi'$ :  $\forall \varphi :: 'v$  literal multiset.  $\varphi \in \text{fst } \psi' \longrightarrow \varphi \in \text{fst } \psi''$ 
    and  $I_{\chi'}$ :  $I \models \chi' \longleftrightarrow I \models \chi^{2'}$ 
    and tot-imp $\chi'$ :  $\forall I'. \text{total-over-m } I' \{ \chi' \} \longrightarrow \text{total-over-m } I' \{ \chi^{2'} \}$ 
    using can-decrease-count[of  $\chi' \text{ Pos v count } \chi' \text{ (Pos v) } \psi' \text{ I}$ ] by auto

  obtain C where  $\chi^2$ :  $\chi^2 = C + \{ \# \text{Neg v} \# \}$  and negC: Neg v  $\notin \# C$  and posC: Pos v  $\notin \# C$ 
    by (metis (no-types, lifting) One-nat-def Posv Suc-inject Suc-pred  $\chi \chi^2 \text{-incl}$  count $\chi^2$ 
      count-diff count-single gr0I insert-DiffM insert-DiffM2 multi-member-skip
      old.nat.distinct(2))

  obtain C' where
     $\chi^{2'}$ :  $\chi^{2'} = C' + \{ \# \text{Pos v} \# \}$  and
    posC': Pos v  $\notin \# C'$  and
    negC': Neg v  $\notin \# C'$ 
  proof -
    assume a1:  $\bigwedge C'. \llbracket \chi^{2'} = C' + \{ \# \text{Pos v} \# \}; \text{Pos v} \notin \# C'; \text{Neg v} \notin \# C' \rrbracket \implies \text{thesis}$ 
    have f2:  $\bigwedge n. (n :: \text{nat}) - n = 0$ 
      by simp
    have Neg v  $\notin \# \chi^{2'} - \{ \# \text{Pos v} \# \}$ 
      using Negv  $\chi' \chi^{2'} \text{-incl}$  by auto
    then show ?thesis
      using f2 a1 by (metis add.commute count $\chi^{2'}$  count-diff count-single insert-DiffM
        less-nat-zero-code zero-less-one)
  qed

  have already-used-inv  $\psi'$ 
    using rtrancplp-inference-preserves-already-used-inv[of  $\psi \psi'$ ] a-u-i inf by blast
  then have a-u-i- $\psi''$ : already-used-inv  $\psi''$ 
    using rtrancplp-inference-preserves-already-used-inv a-u-i inf' unfolding tautology-def
    by simp

  have totC: total-over-m I {C}
    using tot-imp $\chi$  tot $\chi$  tot-over-m-remove[of I Pos v C] negC posC unfolding  $\chi^2$ 

```

```

  by (metis total-over-m-sum uminus-Neg uminus-of-uminus-id)
have totC': total-over-m I {C'}
  using tot-impχ' totχ' total-over-m-sum tot-over-m-remove[of I Neg v C'] negC' posC'
  unfolding χ2' by (metis total-over-m-sum uminus-Neg)
have ¬ I ⊨ C + C'
  using χ Iχ χ' Iχ' unfolding χ2 χ2' true-cls-def Bex-mset-def
  by (metis add-gr-0 count-union true-cls-singleton true-cls-union-increase)
then have part-I-ψ''': partial-interps Leaf I (fst ψ'' ∪ {C + C'})
  using totC totC' by simp
  (metis ¬ I ⊨ C + C' atms-of-ms-singleton total-over-m-def total-over-m-sum)
{
  assume ({#Pos v#} + C', {#Neg v#} + C) ∉ snd ψ''
  then have inf'': inference ψ'' (fst ψ'' ∪ {C + C'}, snd ψ'' ∪ {(χ2', χ2)})
    using add commute φ' χ2incl (χ2' ∈ fst ψ'') unfolding χ2 χ2'
    by (metis prod.collapse inference-step resolution)
  have inference** ψ (fst ψ'' ∪ {C + C'}, snd ψ'' ∪ {(χ2', χ2)})
    using inf inf' inf'' rtranclp-trans by auto
  moreover have sem-tree-size Leaf < sem-tree-size xs unfolding xs by auto
  ultimately have ?case using part-I-ψ''' by (metis fst-conv)
}
moreover {
  assume a: ({#Pos v#} + C', {#Neg v#} + C) ∈ snd ψ''
  then have (∃χ ∈ fst ψ''. (∀I. total-over-m I {C+C'} → total-over-m I {χ})
    ∧ (∀I. total-over-m I {χ} → I ⊨ χ → I ⊨ C' + C))
    ∨ tautology (C' + C)
  proof -
    obtain p where p: Pos p ∈# ({#Pos v#} + C') and
      n: Neg p ∈# ({#Neg v#} + C) and
      decomp: ((∃χ ∈ fst ψ''.
        (∀I. total-over-m I ({#Pos v#} + C') - {#Pos p#}
          + (({#Neg v#} + C) - {#Neg p#}))
        → total-over-m I {χ})
        ∧ (∀I. total-over-m I {χ} → I ⊨ χ
        → I ⊨ ({#Pos v#} + C') - {#Pos p#} + (({#Neg v#} + C) - {#Neg p#})))
        ∨ tautology (({#Pos v#} + C') - {#Pos p#} + (({#Neg v#} + C) - {#Neg p#})))
    using a by (blast intro: allE[OF a-u-i-ψ''[unfolded subsumes-def Ball-def],
      of ({#Pos v#} + C', {#Neg v#} + C)])
  { assume p ≠ v
    then have Pos p ∈# C' ∧ Neg p ∈# C using p n by force
    then have ?thesis by (metis add-gr-0 count-union tautology-Pos-Neg)
  }
  moreover {
    assume p = v
    then have ?thesis using decomp by (metis add commute add-diff-cancel-left')
  }
  ultimately show ?thesis by auto
}
qed
moreover {
  assume ∃χ ∈ fst ψ''. (∀I. total-over-m I {C+C'} → total-over-m I {χ})
    ∧ (∀I. total-over-m I {χ} → I ⊨ χ → I ⊨ C' + C)
  then obtain ∅ where ∅: ∅ ∈ fst ψ'' and
    tot-∅-CC': ∀I. total-over-m I {C+C'} → total-over-m I {∅} and
    ∅-inv: ∀I. total-over-m I {∅} → I ⊨ ∅ → I ⊨ C' + C by blast
  have partial-interps Leaf I (fst ψ'')

```

```

    using tot- $\vartheta$ -CC'  $\vartheta$   $\vartheta$ -inv totC totC'  $\langle \neg I \models C + C' \rangle$  total-over-m-sum by fastforce
    moreover have sem-tree-size Leaf < sem-tree-size xs unfolding xs by auto
    ultimately have ?case by (metis inf inf' rtranclp-trans)
  }
  moreover {
    assume tautCC': tautology (C' + C)
    have total-over-m I {C'+C} using totC totC' total-over-m-sum by auto
    then have  $\neg$ tautology (C' + C)
      using  $\langle \neg I \models C + C' \rangle$  unfolding add.commute[of C C'] total-over-m-def
      unfolding tautology-def by auto
    then have False using tautCC' unfolding tautology-def by auto
  }
  ultimately have ?case by auto
}
ultimately have ?case by auto
}
ultimately have ?case using part by (metis (no-types) sem-tree-size.simps(1))
}
moreover {
  assume size-ag: sem-tree-size ag > 0
  have sem-tree-size ag < sem-tree-size xs unfolding xs by auto
  moreover have partial-interps ag (I  $\cup$  {Pos v}) (fst  $\psi$ )
    and partad: partial-interps ad (I  $\cup$  {Neg v}) (fst  $\psi$ )
    using part partial-interps.simps(2) unfolding xs by metis+
  moreover have sem-tree-size ag < sem-tree-size xs  $\longrightarrow$  finite (fst  $\psi$ )  $\longrightarrow$  already-used-inv  $\psi$ 
     $\longrightarrow$  ( partial-interps ag (I  $\cup$  {Pos v}) (fst  $\psi$ )  $\longrightarrow$ 
      ( $\exists$  tree'  $\psi'$ . inference**  $\psi \psi' \wedge$  partial-interps tree' (I  $\cup$  {Pos v}) (fst  $\psi'$ )
         $\wedge$  (sem-tree-size tree' < sem-tree-size ag  $\vee$  sem-tree-size ag = 0)))
    using IH by auto
  ultimately obtain  $\psi' :: 'v$  state and tree' :: 'v sem-tree where
    inf: inference**  $\psi \psi'$ 
    and part: partial-interps tree' (I  $\cup$  {Pos v}) (fst  $\psi'$ )
    and size: sem-tree-size tree' < sem-tree-size ag  $\vee$  sem-tree-size ag = 0
    using finite part rtranclp.rtrancl-refl a-u-i by blast

  have partial-interps ad (I  $\cup$  {Neg v}) (fst  $\psi'$ )
    using rtranclp-inference-preserve-partial-tree inf partad by metis
  then have partial-interps (Node v tree' ad) I (fst  $\psi'$ ) using part by auto
  then have ?case using inf size size-ag part unfolding xs by fastforce
}
moreover {
  assume size-ad: sem-tree-size ad > 0
  have sem-tree-size ad < sem-tree-size xs unfolding xs by auto
  moreover have partag: partial-interps ag (I  $\cup$  {Pos v}) (fst  $\psi$ ) and
    partial-interps ad (I  $\cup$  {Neg v}) (fst  $\psi$ )
    using part partial-interps.simps(2) unfolding xs by metis+
  moreover have sem-tree-size ad < sem-tree-size xs  $\longrightarrow$  finite (fst  $\psi$ )  $\longrightarrow$  already-used-inv  $\psi$ 
     $\longrightarrow$  ( partial-interps ad (I  $\cup$  {Neg v}) (fst  $\psi$ )
       $\longrightarrow$  ( $\exists$  tree'  $\psi'$ . inference**  $\psi \psi' \wedge$  partial-interps tree' (I  $\cup$  {Neg v}) (fst  $\psi'$ )
         $\wedge$  (sem-tree-size tree' < sem-tree-size ad  $\vee$  sem-tree-size ad = 0)))
    using IH by auto
  ultimately obtain  $\psi' :: 'v$  state and tree' :: 'v sem-tree where
    inf: inference**  $\psi \psi'$ 
    and part: partial-interps tree' (I  $\cup$  {Neg v}) (fst  $\psi'$ )
    and size: sem-tree-size tree' < sem-tree-size ad  $\vee$  sem-tree-size ad = 0

```

```

    using finite part rtrancp.rtrancf-refl a-u-i by blast

  have partial-interps ag ( $I \cup \{Pos\ v\}$ ) (fst  $\psi'$ )
    using rtrancp-inference-preserve-partial-tree inf partag by metis
  then have partial-interps (Node v ag tree') I (fst  $\psi'$ ) using part by auto
  then have ?case using inf size size-ad unfolding xs by fastforce
}
ultimately have ?case by auto
}
ultimately show ?case by auto
qed

lemma inference-completeness-inv:
  fixes  $\psi :: 'v :: linorder\ state$ 
  assumes
    unsat:  $\neg$ satisfiable (fst  $\psi$ ) and
    finite: finite (fst  $\psi$ ) and
    a-u-v: already-used-inv  $\psi$ 
  shows  $\exists \psi'. (inference^{**} \psi \psi' \wedge \{\#\} \in fst \psi')$ 
proof -
  obtain tree where partial-interps tree {} (fst  $\psi$ )
    using partial-interps-build-sem-tree-atms assms by metis
  then show ?thesis
    using unsat finite a-u-v
  proof (induct tree arbitrary:  $\psi$  rule: sem-tree-size)
    case (bigger tree  $\psi$ ) note  $H = this$ 
    {
      fix  $\chi$ 
      assume tree: tree = Leaf
      obtain  $\chi$  where  $\chi: \neg \{\} \models \chi$  and tot $\chi$ : total-over-m {} { $\chi$ } and  $\chi\psi: \chi \in fst \psi$ 
        using H unfolding tree by auto
      moreover have { $\#$ } =  $\chi$ 
        using tot $\chi$  unfolding total-over-m-def total-over-set-def by fastforce
      moreover have inference $^{**}$   $\psi \psi$  by auto
      ultimately have ?case by metis
    }
  moreover {
    fix v tree1 tree2
    assume tree: tree = Node v tree1 tree2
    obtain
      tree'  $\psi'$  where inf: inference $^{**}$   $\psi \psi'$  and
      part': partial-interps tree' {} (fst  $\psi'$ ) and
      decrease: sem-tree-size tree' < sem-tree-size tree  $\vee$  sem-tree-size tree = 0
        using can-decrease-tree-size[of  $\psi$ ] H(2,4,5) unfolding tautology-def by meson
    have sem-tree-size tree' < sem-tree-size tree using decrease unfolding tree by auto
    moreover have finite (fst  $\psi'$ ) using rtrancp-inference-preserves-finite inf H(4) by metis
    moreover have unsatisfiable (fst  $\psi'$ )
      using inference-preserves-unsat inf bigger.prem(2) by blast
    moreover have already-used-inv  $\psi'$ 
      using H(5) inf rtrancp-inference-preserves-already-used-inv[of  $\psi \psi'$ ] by auto
    ultimately have ?case using inf rtrancp-trans part' H(1) by fastforce
  }
  ultimately show ?case by (case-tac tree, auto)
qed
qed

```

```

lemma inference-completeness:
  fixes  $\psi :: 'v :: \text{linorder state}$ 
  assumes unsat:  $\neg \text{satisfiable (fst } \psi)$ 
  and finite: finite (fst } \psi)
  and snd  $\psi = \{\}$ 
  shows  $\exists \psi'. (\text{rtrancpl inference } \psi \ \psi' \wedge \{\#\} \in \text{fst } \psi')$ 
proof –
  have already-used-inv  $\psi$  unfolding assms by auto
  then show ?thesis using assms inference-completeness-inv by blast
qed

```

```

lemma inference-soundness:
  fixes  $\psi :: 'v :: \text{linorder state}$ 
  assumes rtrancpl inference  $\psi \ \psi'$  and  $\{\#\} \in \text{fst } \psi'$ 
  shows unsatisfiable (fst } \psi)
  using assms by (meson rtrancpl-inference-preserves-un-sat satisfiable-def true-cls-empty true-clss-def)

```

```

lemma inference-soundness-and-completeness:
fixes  $\psi :: 'v :: \text{linorder state}$ 
assumes finite: finite (fst } \psi)
and snd  $\psi = \{\}$ 
shows  $(\exists \psi'. (\text{inference}^{**} \ \psi \ \psi' \wedge \{\#\} \in \text{fst } \psi')) \longleftrightarrow \text{unsatisfiable (fst } \psi)$ 
  using assms inference-completeness inference-soundness by metis

```

12.4 Lemma about the simplified state

abbreviation *simplified* $\psi \equiv (\text{no-step simplify } \psi)$

```

lemma simplified-count:
  assumes simp: simplified  $\psi$  and  $\chi: \chi \in \psi$ 
  shows count  $\chi \ L \leq 1$ 
proof –
  {
    let  $? \chi' = \chi - \{\#L, L\# \}$ 
    assume count  $\chi \ L \geq 2$ 
    then have f1: count  $(\chi - \{\#L, L\# \} + \{\#L, L\# \}) \ L = \text{count } \chi \ L$ 
      by simp
    then have  $L \in \# \ \chi - \{\#L\# \}$ 
      by simp
    then have  $\chi'$ :  $? \chi' + \{\#L\# \} + \{\#L\# \} = \chi$ 
      using f1 by (metis (no-types) diff-diff-add diff-single-eq-union union-assoc union-single-eq-member)
    have  $\exists \psi'. \text{simplify } \psi \ \psi'$ 
      by (metis (no-types, hide-lams)  $\chi \ \chi'$  add.commute factoring-imp-simplify union-assoc)
    then have False using simp by auto
  }
  then show ?thesis by arith
qed

```

```

lemma simplified-no-both:
  assumes simp: simplified  $\psi$  and  $\chi: \chi \in \psi$ 
  shows  $\neg (L \in \# \ \chi \wedge \neg L \in \# \ \chi)$ 
proof (rule ccontr)
  assume  $\neg \neg (L \in \# \ \chi \wedge \neg L \in \# \ \chi)$ 

```

```

then have  $L \in \# \chi \wedge - L \in \# \chi$  by metis
then obtain  $\chi'$  where  $\chi = \chi' + \{\#Pos (atm-of L)\# \} + \{\#Neg (atm-of L)\# \}$ 
  by (metis Neg-atm-of-iff Pos-atm-of-iff diff-union-swap insert-DiffM2 uminus-Neg uminus-Pos)
then show False using  $\chi$  simp tautology-deletion by fastforce
qed

```

lemma *simplified-not-tautology*:

```

assumes simplified  $\{\psi\}$ 
shows  $\sim$  tautology  $\psi$ 
proof (rule ccontr)
  assume  $\sim$  ?thesis
  then obtain  $p$  where  $Pos\ p \in \# \psi \wedge Neg\ p \in \# \psi$  using tautology-decomp by metis
  then obtain  $\chi$  where  $\psi = \chi + \{\#Pos\ p\# \} + \{\#Neg\ p\# \}$ 
    by (metis insert-noteq-member literal.distinct(1) multi-member-split)
  then have  $\sim$  simplified  $\{\psi\}$  by (auto intro: tautology-deletion)
  then show False using assms by auto
qed

```

lemma *simplified-remove*:

```

assumes simplified  $\{\psi\}$ 
shows simplified  $\{\psi - \{\#l\#\}\}$ 
proof (rule ccontr)
  assume  $ns: \neg$  simplified  $\{\psi - \{\#l\#\}\}$ 
  {
    assume  $\neg l \in \# \psi$ 
    then have  $\psi - \{\#l\#\} = \psi$  by simp
    then have False using ns assms by auto
  }
  moreover {
    assume  $l\psi: l \in \# \psi$ 
    have  $A: \bigwedge A. A \in \{\psi - \{\#l\#\}\} \longleftrightarrow A + \{\#l\#\} \in \{\psi\}$  by (auto simp add: lψ)
    obtain  $l'$  where  $l':$  simplify  $\{\psi - \{\#l\#\}\}$   $l'$  using ns by metis
    then have  $\exists l'. \text{simplify } \{\psi\} \ l'$ 
    proof (induction rule: simplify.induct)
      case (tautology-deletion  $A\ P$ )
      have  $\{\#Neg\ P\# \} + (\{\#Pos\ P\# \} + (A + \{\#l\#\})) \in \{\psi\}$ 
        by (metis (no-types) A add.commute tautology-deletion.hyps union-lcomm)
      then show ?thesis
        by (metis simplify.tautology-deletion[of A + \{\#l\#\} P \{\psi\}] add.commute)
    next
      case (condensation  $A\ L$ )
      have  $A + \{\#L\#\} + \{\#L\#\} + \{\#l\#\} \in \{\psi\}$ 
        using A condensation.hyps by blast
      then have  $\{\#L, L\#\} + (A + \{\#l\#\}) \in \{\psi\}$ 
        by (metis (no-types) union-assoc union-commute)
      then show ?case
        using factoring-imp-simplify by blast
    next
      case (subsumption  $A\ B$ )
      then show ?case by blast
    qed
  }
  then have False using assms(1) by blast
}
ultimately show False by auto
qed

```

```

lemma in-simplified-simplified:
  assumes simp: simplified  $\psi$  and incl:  $\psi' \subseteq \psi$ 
  shows simplified  $\psi'$ 
proof (rule ccontr)
  assume  $\neg ?thesis$ 
  then obtain  $\psi''$  where simplify  $\psi' \psi''$  by metis
  then have  $\exists l'. \text{simplify } \psi l'$ 
  proof (induction rule: simplify.induct)
    case (tautology-deletion A P)
    then show ?thesis using simplify.tautology-deletion[of A P  $\psi$ ] incl by blast
  next
    case (condensation A L)
    then show ?case using simplify.condensation[of A L  $\psi$ ] incl by blast
  next
    case (subsumption A B)
    then show ?case using simplify.subsumption[of A  $\psi$  B] incl by auto
  qed
  then show False using assms(1) by blast
qed

lemma simplified-in:
  assumes simplified  $\psi$ 
  and  $N \in \psi$ 
  shows simplified  $\{N\}$ 
  using assms by (metis Set.set-insert empty-subsetI in-simplified-simplified insert-mono)

lemma subsumes-imp-formula:
  assumes  $\psi \leq \# \varphi$ 
  shows  $\{\psi\} \models_p \varphi$ 
  unfolding true-clss-cls-def apply auto
  using assms true-cls-mono-leD by blast

lemma simplified-imp-distinct-mset-tauto:
  assumes simp: simplified  $\psi'$ 
  shows distinct-mset-set  $\psi'$  and  $\forall \chi \in \psi'. \neg \text{tautology } \chi$ 
proof -
  show  $\forall \chi \in \psi'. \neg \text{tautology } \chi$ 
  using simp by (auto simp add: simplified-in simplified-not-tautology)

  show distinct-mset-set  $\psi'$ 
  proof (rule ccontr)
    assume  $\neg ?thesis$ 
    then obtain  $\chi$  where  $\chi \in \psi'$  and  $\neg \text{distinct-mset } \chi$  unfolding distinct-mset-set-def by auto
    then obtain L where count  $\chi$  L  $\geq 2$ 
    unfolding distinct-mset-def by (metis gr-implies-not0 le-antisym less-one not-le simp
      simplified-count)
    then show False by (metis Suc-1  $\langle \chi \in \psi' \rangle$  not-less-eq-eq simp simplified-count)
  qed
qed

lemma simplified-no-more-full1-simplified:
  assumes simplified  $\psi$ 
  shows  $\neg \text{full1 simplify } \psi \psi'$ 

```


using *assms* unfolding *full1-def* by (*meson* *trancplD*)

12.5 Resolution and Invariants

inductive *resolution* :: 'v state \Rightarrow 'v state \Rightarrow bool **where**

full1-simp: *full1 simplify* $N\ N' \Longrightarrow \text{resolution } (N, \text{already-used})\ (N', \text{already-used})$ |

inferring: *inference* $(N, \text{already-used})\ (N', \text{already-used}') \Longrightarrow \text{simplified } N$

$\Longrightarrow \text{full simplify } N'\ N'' \Longrightarrow \text{resolution } (N, \text{already-used})\ (N'', \text{already-used}')$

12.5.1 Invariants

lemma *resolution-finite*:

assumes *resolution* $\psi\ \psi'$ **and** *finite* (*fst* ψ)

shows *finite* (*fst* ψ')

using *assms* **by** (*induct* rule: *resolution.induct*)

(*auto simp add*: *full1-def full-def rtrancpl-simplify-preserves-finite*

dest: *trancpl-into-rtrancpl inference-preserves-finite*)

lemma *rtrancpl-resolution-finite*:

assumes *resolution*** $\psi\ \psi'$ **and** *finite* (*fst* ψ)

shows *finite* (*fst* ψ')

using *assms* **by** (*induct* rule: *rtrancpl-induct*, *auto simp add*: *resolution-finite*)

lemma *resolution-finite-snd*:

assumes *resolution* $\psi\ \psi'$ **and** *finite* (*snd* ψ)

shows *finite* (*snd* ψ')

using *assms* **apply** (*induct* rule: *resolution.induct*, *auto simp add*: *inference-preserves-finite-snd*)

using *inference-preserves-finite-snd snd-conv* **by** *metis*

lemma *rtrancpl-resolution-finite-snd*:

assumes *resolution*** $\psi\ \psi'$ **and** *finite* (*snd* ψ)

shows *finite* (*snd* ψ')

using *assms* **by** (*induct* rule: *rtrancpl-induct*, *auto simp add*: *resolution-finite-snd*)

lemma *resolution-always-simplified*:

assumes *resolution* $\psi\ \psi'$

shows *simplified* (*fst* ψ')

using *assms* **by** (*induct* rule: *resolution.induct*)

(*auto simp add*: *full1-def full-def*)

lemma *trancpl-resolution-always-simplified*:

assumes *trancpl resolution* $\psi\ \psi'$

shows *simplified* (*fst* ψ')

using *assms* **by** (*induct* rule: *trancpl.induct*, *auto simp add*: *resolution-always-simplified*)

lemma *resolution-atms-of*:

assumes *resolution* $\psi\ \psi'$ **and** *finite* (*fst* ψ)

shows *atms-of-ms* (*fst* ψ') \subseteq *atms-of-ms* (*fst* ψ)

using *assms* **apply** (*induct* rule: *resolution.induct*)

apply(*simp add*: *rtrancpl-simplify-atms-of-ms trancpl-into-rtrancpl full1-def*)

by (*metis* (*no-types*, *lifting*) *contra-subsetD fst-conv full-def*

inference-preserves-atms-of-ms rtrancpl-simplify-atms-of-ms subsetI)

lemma *rtrancpl-resolution-atms-of*:

assumes *resolution*** $\psi\ \psi'$ **and** *finite* (*fst* ψ)

shows *atms-of-ms* (*fst* ψ') \subseteq *atms-of-ms* (*fst* ψ)

using *assms* **apply** (*induct rule: rtrancpl-induct*)
using *resolution-atms-of rtrancpl-resolution-finite* **by** *blast+*

lemma *resolution-include:*

assumes *res: resolution $\psi \psi'$ and finite: finite (fst ψ)*
shows *fst $\psi' \subseteq \text{build-all-simple-clss (atms-of-ms (fst } \psi))$*

proof –

have *finite': finite (fst $\psi')$* **using** *local.finite res resolution-finite* **by** *blast*
have *simplified (fst $\psi')$* **using** *res finite' resolution-always-simplified* **by** *blast*
then have *fst $\psi' \subseteq \text{build-all-simple-clss (atms-of-ms (fst } \psi'))$*
using *simplified-in-build-all finite' simplified-imp-distinct-mset-tauto[of fst ψ']* **by** *auto*
moreover have *atms-of-ms (fst $\psi') \subseteq \text{atms-of-ms (fst } \psi)$*
using *res finite resolution-atms-of[of $\psi \psi'$]* **by** *auto*
ultimately show *?thesis* **by** (*meson atms-of-ms-finite local.finite order.trans rev-finite-subset build-all-simple-clss-mono*)

qed

lemma *rtrancpl-resolution-include:*

assumes *res: trancpl resolution $\psi \psi'$ and finite: finite (fst ψ)*
shows *fst $\psi' \subseteq \text{build-all-simple-clss (atms-of-ms (fst } \psi))$*
using *assms* **apply** (*induct rule: trancpl.induct*)
apply (*simp add: resolution-include*)
by (*meson atms-of-ms-finite build-all-simple-clss-finite build-all-simple-clss-mono finite-subset resolution-include rtrancpl-resolution-atms-of set-rev-mp subsetI trancpl-into-rtrancpl*)

abbreviation *already-used-all-simple*

:: ('a literal multiset \times 'a literal multiset) set \Rightarrow 'a set \Rightarrow bool **where**

already-used-all-simple already-used vars \equiv

($\forall (A, B) \in \text{already-used. simplified } \{A\} \wedge \text{simplified } \{B\} \wedge \text{atms-of } A \subseteq \text{vars} \wedge \text{atms-of } B \subseteq \text{vars}$)

lemma *already-used-all-simple-vars-incl:*

assumes *vars \subseteq vars'*
shows *already-used-all-simple a vars \implies already-used-all-simple a vars'*
using *assms* **by** *fast*

lemma *inference-clause-preserves-already-used-all-simple:*

assumes *inference-clause $S S'$*
and *already-used-all-simple (snd S) vars*
and *simplified (fst S)*
and *atms-of-ms (fst S) \subseteq vars*
shows *already-used-all-simple (snd (fst $S \cup \{\text{fst } S'\}, \text{snd } S'))$ vars*
using *assms*

proof (*induct rule: inference-clause.induct*)

case (*factoring $L C N$ already-used*)

then show *?case* **by** (*simp add: simplified-in factoring-imp-simplify*)

next

case (*resolution $P C N D$ already-used*) **note** *H = this*

show *?case* **apply** *clarify*

proof –

fix *A B v*

assume *(A, B) \in snd (fst (N , already-used))*

$\cup \{\text{fst } (C + D, \text{already-used} \cup \{(\{\#Pos P\# + C, \{\#Neg P\# + D\})\}),$
 $\text{snd } (C + D, \text{already-used} \cup \{(\{\#Pos P\# + C, \{\#Neg P\# + D\})\})\}$

then have *(A, B) \in already-used \vee (A, B) = ($\{\#Pos P\# + C, \{\#Neg P\# + D\}$)* **by** *auto*
moreover {

```

    assume  $(A, B) \in \text{already-used}$ 
    then have  $\text{simplified } \{A\} \wedge \text{simplified } \{B\} \wedge \text{atms-of } A \subseteq \text{vars} \wedge \text{atms-of } B \subseteq \text{vars}$ 
      using  $H(4)$  by auto
  }
  moreover {
    assume  $\text{eq: } (A, B) = (\{\#Pos\ P\# \} + C, \{\#Neg\ P\# \} + D)$ 
    then have  $\text{simplified } \{A\}$  using  $\text{simplified-in } H(1,5)$  by auto
    moreover have  $\text{simplified } \{B\}$  using  $\text{eq simplified-in } H(2,5)$  by auto
    moreover have  $\text{atms-of } A \subseteq \text{atms-of-ms } N$ 
      using  $\text{eq } H(1) \text{ atms-of-atms-of-ms-mono}[of\ A\ N]$  by auto
    moreover have  $\text{atms-of } B \subseteq \text{atms-of-ms } N$ 
      using  $\text{eq } H(2) \text{ atms-of-atms-of-ms-mono}[of\ B\ N]$  by auto
    ultimately have  $\text{simplified } \{A\} \wedge \text{simplified } \{B\} \wedge \text{atms-of } A \subseteq \text{vars} \wedge \text{atms-of } B \subseteq \text{vars}$ 
      using  $H(6)$  by auto
  }
  ultimately show  $\text{simplified } \{A\} \wedge \text{simplified } \{B\} \wedge \text{atms-of } A \subseteq \text{vars} \wedge \text{atms-of } B \subseteq \text{vars}$ 
    by fast
qed

```

lemma *inference-preserves-already-used-all-simple:*
 assumes *inference* $S\ S'$
 and *already-used-all-simple* $(\text{snd } S)\ \text{vars}$
 and *simplified* $(\text{fst } S)$
 and $\text{atms-of-ms } (\text{fst } S) \subseteq \text{vars}$
 shows *already-used-all-simple* $(\text{snd } S')\ \text{vars}$
 using *assms*
proof (*induct rule: inference.induct*)
 case (*inference-step* S *clause already-used*)
 then show ?case
 using *inference-clause-preserves-already-used-all-simple*[*of* S (*clause*, *already-used*) *vars*]
 by auto
qed

lemma *already-used-all-simple-inv:*
 assumes *resolution* $S\ S'$
 and *already-used-all-simple* $(\text{snd } S)\ \text{vars}$
 and $\text{atms-of-ms } (\text{fst } S) \subseteq \text{vars}$
 shows *already-used-all-simple* $(\text{snd } S')\ \text{vars}$
 using *assms*
proof (*induct rule: resolution.induct*)
 case (*full1-simp* $N\ N'$)
 then show ?case by *simp*
next
 case (*inferring* N *already-used* N' *already-used'* N'')
 then show *already-used-all-simple* $(\text{snd } (N'', \text{already-used'}))\ \text{vars}$
 using *inference-preserves-already-used-all-simple*[*of* $(N, \text{already-used})$] by *simp*
qed

lemma *rtrancplp-already-used-all-simple-inv:*
 assumes *resolution*** $S\ S'$
 and *already-used-all-simple* $(\text{snd } S)\ \text{vars}$
 and $\text{atms-of-ms } (\text{fst } S) \subseteq \text{vars}$
 and *finite* $(\text{fst } S)$
 shows *already-used-all-simple* $(\text{snd } S')\ \text{vars}$

```

using assms
proof (induct rule: rtrancpl-induct)
  case base
  then show ?case by simp
next
  case (step S' S'') note infstar = this(1) and IH = this(3) and res = this(2) and
    already = this(4) and atms = this(5) and finite = this(6)
  have already-used-all-simple (snd S') vars using IH already atms finite by simp
  moreover have atms-of-ms (fst S') ⊆ atms-of-ms (fst S)
    by (simp add: infstar local.finite rtrancpl-resolution-atms-of)
  then have atms-of-ms (fst S') ⊆ vars using atms by auto
  ultimately show ?case
    using already-used-all-simple-inv[OF res] by simp
qed

```

```

lemma inference-clause-simplified-already-used-subset:
  assumes inference-clause S S'
  and simplified (fst S)
  shows snd S ⊆ snd S'
  using assms apply (induct rule: inference-clause.induct, auto)
  using factoring-imp-simplify by blast

```

```

lemma inference-simplified-already-used-subset:
  assumes inference S S'
  and simplified (fst S)
  shows snd S ⊆ snd S'
  using assms apply (induct rule: inference.induct)
  by (metis inference-clause-simplified-already-used-subset snd-conv)

```

```

lemma resolution-simplified-already-used-subset:
  assumes resolution S S'
  and simplified (fst S)
  shows snd S ⊆ snd S'
  using assms apply (induct rule: resolution.induct, simp-all add: full1-def)
  apply (meson trancplD)
  by (metis inference-simplified-already-used-subset fst-conv snd-conv)

```

```

lemma trancpl-resolution-simplified-already-used-subset:
  assumes trancpl resolution S S'
  and simplified (fst S)
  shows snd S ⊆ snd S'
  using assms apply (induct rule: trancpl.induct)
  using resolution-simplified-already-used-subset apply metis
  by (meson trancpl-resolution-always-simplified resolution-simplified-already-used-subset
    less-trans)

```

abbreviation *already-used-top vars* \equiv *build-all-simple-clss vars* \times *build-all-simple-clss vars*

```

lemma already-used-all-simple-in-already-used-top:
  assumes already-used-all-simple s vars and finite vars
  shows s ⊆ already-used-top vars
proof
  fix x
  assume x-s: x ∈ s
  obtain A B where x: x = (A, B) by (case-tac x, auto)

```

then have *simplified* $\{A\}$ **and** *atms-of* $A \subseteq \text{vars}$ **using** *assms*(1) x -s **by** *fastforce+*
then have $A: A \in \text{build-all-simple-clss vars}$
using *build-all-simple-clss-mono*[of vars *atms-of* A] x *assms*(2)
simplified-imp-distinct-mset-tauto[of $\{A\}$]
distinct-mset-not-tautology-implies-in-build-all-simple-clss **by** *fast*
moreover have *simplified* $\{B\}$ **and** *atms-of* $B \subseteq \text{vars}$ **using** *assms*(1) x -s x **by** *fast+*
then have $B: B \in \text{build-all-simple-clss vars}$
using *simplified-imp-distinct-mset-tauto*[of $\{B\}$]
distinct-mset-not-tautology-implies-in-build-all-simple-clss
build-all-simple-clss-mono[of vars *atms-of* B] x *assms*(2) **by** *fast*
ultimately show $x \in \text{build-all-simple-clss vars} \times \text{build-all-simple-clss vars}$
unfolding x **by** *auto*
qed

lemma *already-used-top-finite*:

assumes *finite vars*
shows *finite (already-used-top vars)*
using *build-all-simple-clss-finite assms* **by** *auto*

lemma *already-used-top-increasing*:

assumes $\text{var} \subseteq \text{var}'$ **and** *finite var'*
shows *already-used-top var* \subseteq *already-used-top var'*
using *assms build-all-simple-clss-mono* **by** *auto*

lemma *already-used-all-simple-finite*:

fixes $s :: ('a::\text{linorder literal multiset} \times 'a \text{ literal multiset}) \text{ set}$ **and** $\text{vars} :: 'a \text{ set}$
assumes *already-used-all-simple s vars* **and** *finite vars*
shows *finite s*
using *assms already-used-all-simple-in-already-used-top*[OF *assms*(1)]
rev-finite-subset[OF *already-used-top-finite*[of vars]] **by** *auto*

abbreviation *card-simple vars* $\psi \equiv \text{card (already-used-top vars} - \psi)$

lemma *resolution-card-simple-decreasing*:

assumes *res: resolution $\psi \psi'$*
and *a-u-s: already-used-all-simple (snd ψ) vars*
and *finite-v: finite vars*
and *finite-fst: finite (fst ψ)*
and *finite-snd: finite (snd ψ)*
and *simp: simplified (fst ψ)*
and *atms-of-ms (fst ψ) \subseteq vars*
shows *card-simple vars (snd ψ')* $<$ *card-simple vars (snd ψ)*

proof –

let $?vars = \text{vars}$
let $?top = \text{build-all-simple-clss } ?vars \times \text{build-all-simple-clss } ?vars$
have 1: *card-simple vars (snd ψ)* $= \text{card } ?top - \text{card (snd } \psi)$
using *card-Diff-subset finite-snd already-used-all-simple-in-already-used-top*[OF *a-u-s*]
finite-v **by** *metis*
have *a-u-s'*: *already-used-all-simple (snd ψ') vars*
using *already-used-all-simple-inv res a-u-s assms*(7) **by** *blast*
have *f*: *finite (snd ψ')* **using** *already-used-all-simple-finite a-u-s' finite-v* **by** *auto*
have 2: *card-simple vars (snd ψ')* $= \text{card } ?top - \text{card (snd } \psi')$
using *card-Diff-subset*[OF *f*] *already-used-all-simple-in-already-used-top*[OF *a-u-s' finite-v*]
by *auto*
have *card (already-used-top vars)* $\geq \text{card (snd } \psi')$

```

    using already-used-all-simple-in-already-used-top[OF a-u-s' finite-v]
    card-mono[of already-used-top vars snd  $\psi'$ ] already-used-top-finite[OF finite-v] by metis
  then show ?thesis
    using psubset-card-mono[OF f resolution-simplified-already-used-subset[OF res simp]]
    unfolding 1 2 by linarith
qed

```

lemma *tranclp-resolution-card-simple-decreasing*:

```

  assumes tranclp resolution  $\psi \psi'$  and finite-fst: finite (fst  $\psi$ )
  and already-used-all-simple (snd  $\psi$ ) vars
  and atms-of-ms (fst  $\psi$ )  $\subseteq$  vars
  and finite-v: finite vars
  and finite-snd: finite (snd  $\psi$ )
  and simplified (fst  $\psi$ )
  shows card-simple vars (snd  $\psi'$ ) < card-simple vars (snd  $\psi$ )
  using assms
proof (induct rule: tranclp.induct)
  case (r-into-trancl  $\psi \psi'$ )
  then show ?case by (simp add: resolution-card-simple-decreasing)
next
  case (trancl-into-trancl  $\psi \psi' \psi''$ ) note res = this(1) and res' = this(3) and a-u-s = this(5) and
    atms = this(6) and f-v = this(7) and f-fst = this(4) and H = this
  then have card-simple vars (snd  $\psi'$ ) < card-simple vars (snd  $\psi$ ) by auto
  moreover have a-u-s': already-used-all-simple (snd  $\psi'$ ) vars
    using rtranclp-already-used-all-simple-inv[OF tranclp-into-rtranclp[OF res] a-u-s atms f-fst] .
  have finite (fst  $\psi'$ )
    by (meson build-all-simple-clss-finite rev-finite-subset rtranclp-resolution-include
      trancl-into-trancl.hyps(1) trancl-into-trancl.prem(1))
  moreover have finite (snd  $\psi'$ ) using already-used-all-simple-finite[OF a-u-s' f-v] .
  moreover have simplified (fst  $\psi'$ ) using res tranclp-resolution-always-simplified by blast
  moreover have atms-of-ms (fst  $\psi'$ )  $\subseteq$  vars
    by (meson atms f-fst order.trans res rtranclp-resolution-atms-of tranclp-into-rtranclp)
  ultimately show ?case
    using resolution-card-simple-decreasing[OF res' a-u-s' f-v] f-v
    less-trans[of card-simple vars (snd  $\psi''$ ) card-simple vars (snd  $\psi'$ )
      card-simple vars (snd  $\psi$ )]
    by blast
qed

```

lemma *tranclp-resolution-card-simple-decreasing-2*:

```

  assumes tranclp resolution  $\psi \psi'$ 
  and finite-fst: finite (fst  $\psi$ )
  and empty-snd: snd  $\psi$  = {}
  and simplified (fst  $\psi$ )
  shows card-simple (atms-of-ms (fst  $\psi$ )) (snd  $\psi'$ ) < card-simple (atms-of-ms (fst  $\psi$ )) (snd  $\psi$ )
proof -
  let ?vars = (atms-of-ms (fst  $\psi$ ))
  have already-used-all-simple (snd  $\psi$ ) ?vars unfolding empty-snd by auto
  moreover have atms-of-ms (fst  $\psi$ )  $\subseteq$  ?vars by auto
  moreover have finite-v: finite ?vars using finite-fst by auto
  moreover have finite-snd: finite (snd  $\psi$ ) unfolding empty-snd by auto
  ultimately show ?thesis
    using assms(1,2,4) tranclp-resolution-card-simple-decreasing[of  $\psi \psi'$ ] by presburger

```

qed

12.5.2 well-foundness if the relation

lemma *wf-simplified-resolution*:

assumes *f-vars*: *finite vars*

shows *wf* $\{(y:: 'v:: \text{linorder state}, x). (\text{atms-of-ms } (fst\ x) \subseteq \text{vars} \wedge \text{simplified } (fst\ x) \wedge \text{finite } (snd\ x) \wedge \text{finite } (fst\ x) \wedge \text{already-used-all-simple } (snd\ x)\ \text{vars}) \wedge \text{resolution } x\ y\}$

proof –

```
{
  fix a b :: 'v::linorder state
  assume (b, a) ∈ {(y, x). (atms-of-ms (fst x) ⊆ vars ∧ simplified (fst x) ∧ finite (snd x)
    ∧ finite (fst x) ∧ already-used-all-simple (snd x) vars) ∧ resolution x y}
  then have
    atms-of-ms (fst a) ⊆ vars and
    simp: simplified (fst a) and
    finite (snd a) and
    finite (fst a) and
    a-u-v: already-used-all-simple (snd a) vars and
    res: resolution a b by auto
  have finite (already-used-top vars) using f-vars already-used-top-finite by blast
  moreover have already-used-top vars ⊆ already-used-top vars by auto
  moreover have snd b ⊆ already-used-top vars
    using already-used-all-simple-in-already-used-top[of snd b vars]
    a-u-v already-used-all-simple-inv[OF res] (finite (fst a)) (atms-of-ms (fst a) ⊆ vars) f-vars
    by presburger
  moreover have snd a ⊂ snd b using resolution-simplified-already-used-subset[OF res simp] .
  ultimately have finite (already-used-top vars) ∧ already-used-top vars ⊆ already-used-top vars
    ∧ snd b ⊆ already-used-top vars ∧ snd a ⊂ snd b by metis
}
then show ?thesis using wf-bounded-set[of {(y:: 'v:: linorder state, x).
  (atms-of-ms (fst x) ⊆ vars
  ∧ simplified (fst x) ∧ finite (snd x) ∧ finite (fst x) ∧ already-used-all-simple (snd x) vars)
  ∧ resolution x y} λ-. already-used-top vars snd] by auto
```

qed

lemma *wf-simplified-resolution'*:

assumes *f-vars*: *finite vars*

shows *wf* $\{(y:: 'v:: \text{linorder state}, x). (\text{atms-of-ms } (fst\ x) \subseteq \text{vars} \wedge \neg \text{simplified } (fst\ x) \wedge \text{finite } (snd\ x) \wedge \text{finite } (fst\ x) \wedge \text{already-used-all-simple } (snd\ x)\ \text{vars}) \wedge \text{resolution } x\ y\}$

unfolding *wf-def*

apply (*simp add: resolution-always-simplified*)

by (*metis (mono-tags, hide-lams) fst-conv resolution-always-simplified*)

lemma *wf-resolution*:

assumes *f-vars*: *finite vars*

shows *wf* $\{(y:: 'v:: \text{linorder state}, x). (\text{atms-of-ms } (fst\ x) \subseteq \text{vars} \wedge \text{simplified } (fst\ x) \wedge \text{finite } (snd\ x) \wedge \text{finite } (fst\ x) \wedge \text{already-used-all-simple } (snd\ x)\ \text{vars}) \wedge \text{resolution } x\ y\} \cup \{(y, x). (\text{atms-of-ms } (fst\ x) \subseteq \text{vars} \wedge \neg \text{simplified } (fst\ x) \wedge \text{finite } (snd\ x) \wedge \text{finite } (fst\ x) \wedge \text{already-used-all-simple } (snd\ x)\ \text{vars}) \wedge \text{resolution } x\ y\}$ (**is** *wf* (*?R* \cup *?S*))

proof –

have *Domain ?R Int Range ?S = {}* **using** *resolution-always-simplified* **by** *auto blast*

then show *wf* (*?R* \cup *?S*)

using *wf-simplified-resolution[OF f-vars] wf-simplified-resolution'[OF f-vars] wf-Un[of ?R ?S]*

by *fast*

qed

```

lemma rtranclp-simplify-already-used-inv:
  assumes simplify** S S'
  and already-used-inv (S, N)
  shows already-used-inv (S', N)
  using assms apply induction
  using simplify-preserves-already-used-inv by fast+

lemma full1-simplify-already-used-inv:
  assumes full1 simplify S S'
  and already-used-inv (S, N)
  shows already-used-inv (S', N)
  using assms tranclp-into-rtranclp[of simplify S S'] rtranclp-simplify-already-used-inv
  unfolding full1-def by fast

lemma full-simplify-already-used-inv:
  assumes full simplify S S'
  and already-used-inv (S, N)
  shows already-used-inv (S', N)
  using assms rtranclp-simplify-already-used-inv unfolding full-def by fast

lemma resolution-already-used-inv:
  assumes resolution S S'
  and already-used-inv S
  shows already-used-inv S'
  using assms

proof induction
  case (full1-simp N N' already-used)
  then show ?case using full1-simplify-already-used-inv by fast
next
  case (inferring N already-used N' already-used' N'') note inf = this(1) and full = this(3) and
    a-u-v = this(4)
  then show ?case
    using inference-preserves-already-used-inv[OF inf a-u-v] full-simplify-already-used-inv full
    by fast
qed

lemma rtranclp-resolution-already-used-inv:
  assumes resolution** S S'
  and already-used-inv S
  shows already-used-inv S'
  using assms apply induction
  using resolution-already-used-inv by fast+

lemma rtanclp-simplify-preserves-unsat:
  assumes simplify**  $\psi$   $\psi'$ 
  shows satisfiable  $\psi' \longrightarrow$  satisfiable  $\psi$ 
  using assms apply induction
  using simplify-clause-preserves-sat by blast+

lemma full1-simplify-preserves-unsat:
  assumes full1 simplify  $\psi$   $\psi'$ 
  shows satisfiable  $\psi' \longrightarrow$  satisfiable  $\psi$ 
  using assms rtanclp-simplify-preserves-unsat[of  $\psi$   $\psi'$ ] tranclp-into-rtranclp
  unfolding full1-def by metis

```



```

lemma full-simplify-preserves-unsat:
  assumes full simplify  $\psi$   $\psi'$ 
  shows satisfiable  $\psi' \longrightarrow$  satisfiable  $\psi$ 
  using assms rtrancpl-simplify-preserves-unsat[of  $\psi$   $\psi'$ ] unfolding full-def by metis

lemma resolution-preserves-unsat:
  assumes resolution  $\psi$   $\psi'$ 
  shows satisfiable (fst  $\psi'$ )  $\longrightarrow$  satisfiable (fst  $\psi$ )
  using assms apply (induct rule: resolution.induct)
  using full1-simplify-preserves-unsat apply (metis fst-conv)
  using full-simplify-preserves-unsat simplify-preserves-unsat by fastforce

lemma rtrancpl-resolution-preserves-unsat:
  assumes resolution**  $\psi$   $\psi'$ 
  shows satisfiable (fst  $\psi'$ )  $\longrightarrow$  satisfiable (fst  $\psi$ )
  using assms apply induction
  using resolution-preserves-unsat by fast+

lemma rtrancpl-simplify-preserve-partial-tree:
  assumes simplify**  $N$   $N'$ 
  and partial-interps  $t$   $I$   $N$ 
  shows partial-interps  $t$   $I$   $N'$ 
  using assms apply (induction, simp)
  using simplify-preserve-partial-tree by metis

lemma full1-simplify-preserve-partial-tree:
  assumes full1 simplify  $N$   $N'$ 
  and partial-interps  $t$   $I$   $N$ 
  shows partial-interps  $t$   $I$   $N'$ 
  using assms rtrancpl-simplify-preserve-partial-tree[of  $N$   $N'$   $t$   $I$ ] trancpl-into-rtrancpl
  unfolding full1-def by fast

lemma full-simplify-preserve-partial-tree:
  assumes full simplify  $N$   $N'$ 
  and partial-interps  $t$   $I$   $N$ 
  shows partial-interps  $t$   $I$   $N'$ 
  using assms rtrancpl-simplify-preserve-partial-tree[of  $N$   $N'$   $t$   $I$ ] trancpl-into-rtrancpl
  unfolding full-def by fast

lemma resolution-preserve-partial-tree:
  assumes resolution  $S$   $S'$ 
  and partial-interps  $t$   $I$  (fst  $S$ )
  shows partial-interps  $t$   $I$  (fst  $S'$ )
  using assms apply induction
  using full1-simplify-preserve-partial-tree fst-conv apply metis
  using full-simplify-preserve-partial-tree inference-preserve-partial-tree by fastforce

lemma rtrancpl-resolution-preserve-partial-tree:
  assumes resolution**  $S$   $S'$ 
  and partial-interps  $t$   $I$  (fst  $S$ )
  shows partial-interps  $t$   $I$  (fst  $S'$ )
  using assms apply induction
  using resolution-preserve-partial-tree by fast+
  thm nat-less-induct nat.induct

```

```

lemma nat-ge-induct[case-names 0 Suc]:
  assumes  $P\ 0$ 
  and  $(\bigwedge n. (\bigwedge m. m < \text{Suc } n \implies P\ m) \implies P\ (\text{Suc } n))$ 
  shows  $P\ n$ 
  using assms apply (induct rule: nat-less-induct)
  by (case-tac n) auto

lemma wf-always-more-step-False:
  assumes wf R
  shows  $(\forall x. \exists z. (z, x) \in R) \implies \text{False}$ 
  using assms unfolding wf-def by (meson Domain.DomainI assms wfE-min)

lemma finite-finite-mset-element-of-mset[simp]:
  assumes finite N
  shows finite  $\{f\ \varphi\ L \mid \varphi\ L. \varphi \in N \wedge L \in \# \varphi \wedge P\ \varphi\ L\}$ 
  using assms
proof (induction N rule: finite-induct)
  case empty
  show ?case by auto
next
  case (insert x N) note finite = this(1) and IH = this(3)
  have  $\{f\ \varphi\ L \mid \varphi\ L. (\varphi = x \vee \varphi \in N) \wedge L \in \# \varphi \wedge P\ \varphi\ L\} \subseteq \{f\ x\ L \mid L. L \in \# x \wedge P\ x\ L\}$ 
     $\cup \{f\ \varphi\ L \mid \varphi\ L. \varphi \in N \wedge L \in \# \varphi \wedge P\ \varphi\ L\}$  by auto
  moreover have finite  $\{f\ x\ L \mid L. L \in \# x\}$  by auto
  ultimately show ?case using IH finite-subset by fastforce
qed

value card
value filter-mset
value  $\{\# \text{count } \varphi\ L \mid L \in \# \varphi. 2 \leq \text{count } \varphi\ L\ \#\}$ 
value  $(\lambda \varphi. \text{msetsum } \{\# \text{count } \varphi\ L \mid L \in \# \varphi. 2 \leq \text{count } \varphi\ L\ \# \})$ 

syntax
  -comprehension1'-mset :: 'a  $\Rightarrow$  'b  $\Rightarrow$  'b multiset  $\Rightarrow$  'a multiset
    (( $\{\# \cdot / \cdot - : \text{setof } \cdot \#\}$ )))
translations
   $\{\# e. x : \text{setof } M\ \#\} == \text{CONST set-mset } (\text{CONST image-mset } (\%x. e) M)$ 
value  $\{\# a. a : \text{setof } \{\# 1, 1, 2 :: \text{int}\} \#\} = \{1, 2\}$ 

definition sum-count-ge-2 :: 'a multiset set  $\Rightarrow$  nat ( $\Xi$ ) where
sum-count-ge-2  $\equiv \text{folding.F } (\lambda \varphi. \text{op} + (\text{msetsum } \{\# \text{count } \varphi\ L \mid L \in \# \varphi. 2 \leq \text{count } \varphi\ L\ \# \}))\ 0$ 

interpretation sum-count-ge-2:
  folding  $(\lambda \varphi. \text{op} + (\text{msetsum } \{\# \text{count } \varphi\ L \mid L \in \# \varphi. 2 \leq \text{count } \varphi\ L\ \# \}))\ 0$ 
rewrites
  folding.F  $(\lambda \varphi. \text{op} + (\text{msetsum } \{\# \text{count } \varphi\ L \mid L \in \# \varphi. 2 \leq \text{count } \varphi\ L\ \# \}))\ 0 = \text{sum-count-ge-2}$ 
proof -
  show folding  $(\lambda \varphi. \text{op} + (\text{msetsum } (\text{image-mset } (\text{count } \varphi) \{\# L : \# \varphi. 2 \leq \text{count } \varphi\ L\ \# \})))$ 
    by standard auto
  then interpret sum-count-ge-2:
    folding  $(\lambda \varphi. \text{op} + (\text{msetsum } \{\# \text{count } \varphi\ L \mid L \in \# \varphi. 2 \leq \text{count } \varphi\ L\ \# \}))\ 0 .$ 
  show folding.F  $(\lambda \varphi. \text{op} + (\text{msetsum } (\text{image-mset } (\text{count } \varphi) \{\# L : \# \varphi. 2 \leq \text{count } \varphi\ L\ \# \})))\ 0$ 
     $= \text{sum-count-ge-2}$  by (auto simp add: sum-count-ge-2-def)

```

qed

lemma *finite-incl-le-setsum*:

finite ($B :: 'a$ multiset set) $\implies A \subseteq B \implies \Xi A \leq \Xi B$

proof (*induction arbitrary:A rule: finite-induct*)

case *empty*

then show ?case by *simp*

next

case (*insert a F*) note *finite = this(1)* and *aF = this(2)* and *IH = this(3)* and *AF = this(4)*

show ?case

proof (*cases a ∈ A*)

assume $a \notin A$

then have $A \subseteq F$ using *AF* by *auto*

then show ?case using *IH[of A]* by (*simp add: aF local.finite*)

next

assume *aA*: $a \in A$

then have $A - \{a\} \subseteq F$ using *AF* by *auto*

then have $\Xi (A - \{a\}) \leq \Xi F$ using *IH* by *blast*

then show ?case

proof –

obtain *nn* :: $\text{nat} \Rightarrow \text{nat} \Rightarrow \text{nat}$ where

$\forall x0\ x1. (\exists v2. x0 = x1 + v2) = (x0 = x1 + nn\ x0\ x1)$

by *moura*

then have $\Xi F = \Xi (A - \{a\}) + nn\ (\Xi F)\ (\Xi (A - \{a\}))$

using *Nat.le-iff-add* $\langle \Xi (A - \{a\}) \leq \Xi F \rangle$ by *presburger*

then show ?thesis

by (*metis* (*no-types*) *Nat.le-iff-add* *aA* *aF* *add.assoc* *finite.insertI* *finite-subset* *insert.premis* *local.finite* *sum-count-ge-2.insert* *sum-count-ge-2.remove*)

qed

qed

qed

lemma *mset-condensation1*:

$\{\# La : \# A + \{\# L\#\}. 2 \leq \text{count } (A + \{\# L\#\})\ La\#\} = \{\# La : \# A. La \neq L \wedge 2 \leq \text{count } A\ La\#\}$

$\# \cup (\text{if } \text{count } A\ L \geq 1 \text{ then } \text{replicate-mset } (\text{count } A\ L + 1)\ L \text{ else } \{\#\})$

by (*auto intro: multiset-eqI*)

lemma *mset-condensation2*:

$\{\# La : \# A + \{\# L\#\} + \{\# L\#\}. 2 \leq \text{count } (A + \{\# L\#\} + \{\# L\#\})\ La\#\} = \{\# La : \# A. La \neq L \wedge$

$2 \leq \text{count } A\ La\#\} \# \cup (\text{replicate-mset } (\text{count } A\ L + 2)\ L)$

by (*auto intro: multiset-eqI*)

lemma *msetsum-disjoint*:

assumes $A \# \cap B = \{\#\}$

shows $(\sum La \in \# A \# \cup B. f\ La) =$

$(\sum La \in \# A. f\ La) + (\sum La \in \# B. f\ La)$

by (*metis* *assms* *diff-zero* *empty-sup* *image-mset-union* *msetsum.union* *multiset-inter-commute* *multiset-union-diff-commute* *sup-subset-mset-def* *zero-diff*)

lemma *msetsum-linear[simp]*:

fixes $C\ D :: 'a \Rightarrow 'b :: \{\text{comm-monoid-add}\}$

shows $(\sum x \in \# A. C\ x + D\ x) = (\sum x \in \# A. C\ x) + (\sum x \in \# A. D\ x)$

by (*induction A*) (*auto simp: ac-simps*)

lemma *msetsum-if-eq[simp]*: $(\sum x \in \#A. \text{if } L = x \text{ then } 1 \text{ else } 0) = \text{count } A \ L$
by (*induction A*) *auto*

lemma *filter-equality-in-mset*:
filter-mset (op = L) A = replicate-mset (count A L) L
by (*auto simp: multiset-eq-iff*)

lemma *comprehension-mset-False[simp]*:
 $\{\# L \in \# A. \text{False}\} = \{\#\}$
by (*auto simp: multiset-eq-iff*)

lemma *simplify-finite-measure-decrease*:
simplify N N' \implies finite N \implies card N' + Ξ N' < card N + Ξ N
proof (*induction rule: simplify.induct*)
case (*tautology-deletion A P*) **note** *an = this(1)* **and** *fin = this(2)*
let $?N' = N - \{A + \{\#Pos \ P\} + \{\#Neg \ P\}\}$
have *card ?N' < card N*
by (*meson card-Diff1-less tautology-deletion.hyps tautology-deletion.prems*)
moreover **have** $?N' \subseteq N$ **by** *auto*
then **have** *sum-count-ge-2 ?N' \leq sum-count-ge-2 N* **using** *finite-incl-le-setsum[OF fin]* **by** *blast*
ultimately **show** *?case* **by** *linarith*

next

case (*condensation A L*) **note** *AN = this(1)* **and** *fin = this(2)*
let $?C' = A + \{\#L\}$
let $?C = A + \{\#L\} + \{\#L\}$
let $?N' = N - \{?C\} \cup \{?C'\}$
have *card ?N' \leq card N*
using *AN* **by** (*metis (no-types, lifting) Diff-subset Un-empty-right Un-insert-right card.remove card-insert-if card-mono fin finite-Diff order-refl*)
moreover **have** $\Xi \{?C'\} < \Xi \{?C\}$

proof –

have *mset-decomp*:
 $\{\# La \in \# A. (L = La \longrightarrow \text{Suc } 0 \leq \text{count } A \ La) \wedge (L \neq La \longrightarrow 2 \leq \text{count } A \ La)\} =$
 $= \{\# La \in \# A. L \neq La \wedge 2 \leq \text{count } A \ La\} +$
 $\{\# La \in \# A. L = La \wedge \text{Suc } 0 \leq \text{count } A \ L\}$
by (*auto simp: multiset-eq-iff ac-simps*)

have *mset-decomp2*: $\{\# La \in \# A. L \neq La \longrightarrow 2 \leq \text{count } A \ La\} =$
 $\{\# La \in \# A. L \neq La \wedge 2 \leq \text{count } A \ La\} + \text{replicate-mset (count } A \ L) L$
by (*auto simp: multiset-eq-iff*)

show *?thesis*

by (*auto simp: mset-decomp mset-decomp2 filter-equality-in-mset ac-simps*)

qed

have $\Xi ?N' < \Xi N$

proof *cases*

assume *a1: ?C' \in N*

then **show** *?thesis*

proof –

have *f2*: $\bigwedge m \ M. \text{insert } (m::'a \text{ literal multiset}) (M - \{m\}) = M \cup \{m\} \vee m \notin M$

using *Un-empty-right insert-Diff* **by** *blast*

have *f3*: $\bigwedge m \ M \ Ma. \text{insert } (m::'a \text{ literal multiset}) M - \text{insert } m \ Ma = M - \text{insert } m \ Ma$

by *simp*

then **have** *f4*: $\bigwedge M \ m. M - \{m::'a \text{ literal multiset}\} = M \cup \{m\} \vee m \in M$

```

    using Diff-insert-absorb Un-empty-right by fastforce
  have f5: insert (A + {#L#} + {#L#}) N = N
    using f3 f2 Un-empty-right condensation.hyps insert-iff by fastforce
  have  $\bigwedge m M. \text{insert } (m::'a \text{ literal multiset}) M = M \cup \{ \} \vee m \notin M$ 
    using f3 f2 Un-empty-right add.right-neutral insert-iff by fastforce
  then have  $\Xi (N - \{A + \{#L\# \} + \{#L\# \}) < \Xi N$ 
    using f5 f4 by (metis Un-empty-right  $\langle \Xi \{A + \{#L\# \} < \Xi \{A + \{#L\# \} + \{#L\# \} \rangle$ 
      add.right-neutral add-diff-cancel-left' add-gr-0 diff-less fin finite.emptyI not-le
      sum-count-ge-2.empty sum-count-ge-2.insert-remove trans-le-add2)
  then show ?thesis
    using f3 f2 a1 by (metis (no-types) Un-empty-right Un-insert-right condensation.hyps
      insert-iff multi-self-add-other-not-self)
qed
next
assume  $?C' \notin N$ 
have mset-decomp:
   $\{ \# La \in \# A. (L = La \longrightarrow \text{Suc } 0 \leq \text{count } A La) \wedge (L \neq La \longrightarrow 2 \leq \text{count } A La) \# \}$ 
  =  $\{ \# La \in \# A. L \neq La \wedge 2 \leq \text{count } A La \# \} +$ 
   $\{ \# La \in \# A. L = La \wedge \text{Suc } 0 \leq \text{count } A L \# \}$ 
  by (auto simp: multiset-eq-iff ac-simps)
have mset-decomp2:  $\{ \# La \in \# A. L \neq La \longrightarrow 2 \leq \text{count } A La \# \} =$ 
   $\{ \# La \in \# A. L \neq La \wedge 2 \leq \text{count } A La \# \} + \text{replicate-mset } (\text{count } A L) L$ 
  by (auto simp: multiset-eq-iff)

show ?thesis
  using  $\langle \Xi \{A + \{#L\# \} < \Xi \{A + \{#L\# \} + \{#L\# \} \rangle$  condensation.hyps fin
    sum-count-ge-2.remove[of - A + {#L#} + {#L#}]  $\langle ?C' \notin N \rangle$ 
  by (auto simp: mset-decomp mset-decomp2 filter-equality-in-mset)
qed
ultimately show ?case by linarith
next
case (subsumption A B) note AN = this(1) and AB = this(2) and BN = this(3) and fin = this(4)
have card (N - {B}) < card N using BN by (meson card-Diff1-less subsumption.prem)
moreover have  $\Xi (N - \{B\}) \leq \Xi N$ 
  by (simp add: Diff-subset finite-incl-le-setsum subsumption.prem)
ultimately show ?case by linarith
qed

lemma simplify-terminates:
  wf  $\{ (N', N). \text{finite } N \wedge \text{simplify } N N' \}$ 
  using assms apply (rule wfP-if-measure[of finite simplify  $\lambda N. \text{card } N + \Xi N$ ])
  using simplify-finite-measure-decrease by blast

lemma wf-terminates:
  assumes wf r
  shows  $\exists N'. (N', N) \in r^* \wedge (\forall N''. (N'', N') \notin r)$ 
proof -
  let ?P =  $\lambda N. (\exists N'. (N', N) \in r^* \wedge (\forall N''. (N'', N') \notin r))$ 
  have  $(\forall x. (\forall y. (y, x) \in r \longrightarrow ?P y) \longrightarrow ?P x)$ 
  proof clarify
    fix x
    assume H:  $\forall y. (y, x) \in r \longrightarrow ?P y$ 
    { assume  $\exists y. (y, x) \in r$ 

```

```

    then obtain  $y$  where  $y: (y, x) \in r$  by blast
    then have  $?P\ y$  using  $H$  by blast
    then have  $?P\ x$  using  $y$  by (meson rtrancl.rtrancl-into-rtrancl)
  }
  moreover {
    assume  $\neg(\exists y. (y, x) \in r)$ 
    then have  $?P\ x$  by auto
  }
  ultimately show  $?P\ x$  by blast
qed
moreover have  $(\forall x. (\forall y. (y, x) \in r \longrightarrow ?P\ y) \longrightarrow ?P\ x) \longrightarrow \text{All } ?P$ 
  using assms unfolding wf-def by (rule allE)
ultimately have  $\text{All } ?P$  by blast
then show  $?P\ N$  by blast
qed

```

lemma *rtrancl-simplify-terminates*:

```

  assumes fin: finite N
  shows  $\exists N'. \text{simplify}^{**}\ N\ N' \wedge \text{simplified } N'$ 
proof -
  have  $H: \{(N', N). \text{finite } N \wedge \text{simplify } N\ N'\} = \{(N', N). \text{simplify } N\ N' \wedge \text{finite } N\}$  by auto
  then have wf:  $\text{wf } \{(N', N). \text{simplify } N\ N' \wedge \text{finite } N\}$ 
    using simplify-terminates by (simp add: H)
  obtain  $N'$  where  $N': (N', N) \in \{(b, a). \text{simplify } a\ b \wedge \text{finite } a\}^*$  and
    more:  $(\forall N''. (N'', N') \notin \{(b, a). \text{simplify } a\ b \wedge \text{finite } a\})$ 
    using Prop-Resolution.wf-terminates[OF wf, of N] by blast
  have 1:  $\text{simplify}^{**}\ N\ N'$ 
    using  $N'$  by (induction rule: rtrancl.induct) auto
  then have finite N' using fin rtrancl-simplify-preserves-finite by blast
  then have 2:  $\forall N''. \neg \text{simplify } N'\ N''$  using more by auto

  show ?thesis using 1 2 by blast
qed

```

lemma *finite-simplified-full1-simp*:

```

  assumes finite N
  shows  $\text{simplified } N \vee (\exists N'. \text{full1 simplify } N\ N')$ 
  using rtrancl-simplify-terminates[OF assms] unfolding full1-def
  by (metis Nitpick.rtrancl-unfold)

```

lemma *finite-simplified-full-simp*:

```

  assumes finite N
  shows  $\exists N'. \text{full simplify } N\ N'$ 
  using rtrancl-simplify-terminates[OF assms] unfolding full-def by metis

```

lemma *can-decrease-tree-size-resolution*:

```

  fixes  $\psi :: 'v \text{ state}$  and  $\text{tree} :: 'v \text{ sem-tree}$ 
  assumes finite (fst  $\psi$ ) and already-used-inv  $\psi$ 
  and partial-interps tree I (fst  $\psi$ )
  and simplified (fst  $\psi$ )
  shows  $\exists (\text{tree}' :: 'v \text{ sem-tree}) \psi'. \text{resolution}^{**}\ \psi\ \psi' \wedge \text{partial-interps tree}'\ I\ (\text{fst } \psi')$ 
     $\wedge (\text{sem-tree-size tree}' < \text{sem-tree-size tree} \vee \text{sem-tree-size tree} = 0)$ 
  using assms
proof (induct arbitrary: I rule: sem-tree-size)
  case (bigger xs I) note  $IH = \text{this}(1)$  and finite = this(2) and a-u-i = this(3) and part = this(4)

```

and *simp* = *this*(5)

```
{ assume sem-tree-size xs = 0
  then have ?case using part by blast
}
```

moreover {

```
  assume sn0: sem-tree-size xs > 0
  obtain ag ad v where xs: xs = Node v ag ad using sn0 by (case-tac xs, auto)
  {
    assume sem-tree-size ag = 0  $\wedge$  sem-tree-size ad = 0
    then have ag: ag = Leaf and ad: ad = Leaf by (case-tac ag, auto, case-tac ad, auto)
```

then obtain $\chi \chi'$ where

```
 $\chi$ :  $\neg I \cup \{Pos\ v\} \models \chi$  and
 $tot\chi$ : total-over-m ( $I \cup \{Pos\ v\}$ )  $\{\chi\}$  and
 $\chi\psi$ :  $\chi \in fst\ \psi$  and
 $\chi'$ :  $\neg I \cup \{Neg\ v\} \models \chi'$  and
 $tot\chi'$ : total-over-m ( $I \cup \{Neg\ v\}$ )  $\{\chi'\}$  and  $\chi'\psi$ :  $\chi' \in fst\ \psi$ 
using part unfolding xs by auto
```

have *Posv*: *Pos v* $\notin \# \chi$ using χ unfolding *true-cls-def true-lit-def* by *auto*

have *Negv*: *Neg v* $\notin \# \chi'$ using χ' unfolding *true-cls-def true-lit-def* by *auto*

```
{
  assume Negχ:  $\neg Neg\ v \in \# \chi$ 
  then have  $\neg I \models \chi$  using  $\chi$  Posv unfolding true-cls-def true-lit-def by auto
  moreover have total-over-m I  $\{\chi\}$ 
    using Posv Negχ atm-imp-pos-or-neg-lit totχ unfolding total-over-m-def total-over-set-def
    by fastforce
  ultimately have partial-interps Leaf I (fst ψ)
  and sem-tree-size Leaf < sem-tree-size xs
  and resolution** ψ ψ
    unfolding xs by (auto simp add: χψ)
}
```

moreover {

```
  assume Posχ:  $\neg Pos\ v \in \# \chi'$ 
  then have  $I\chi$ :  $\neg I \models \chi'$  using  $\chi'$  Posv unfolding true-cls-def true-lit-def by auto
  moreover have total-over-m I  $\{\chi'\}$ 
    using Negv Posχ atm-imp-pos-or-neg-lit totχ'
    unfolding total-over-m-def total-over-set-def by fastforce
  ultimately have partial-interps Leaf I (fst ψ)
  and sem-tree-size Leaf < sem-tree-size xs
  and resolution** ψ ψ using  $\chi'\psi\ I\chi$  unfolding xs by auto
```

}

moreover {

```
  assume neg: Neg v  $\in \# \chi$  and pos: Pos v  $\in \# \chi'$ 
  have count χ (Neg v) = 1
    using simplified-count[OF simp χψ] neg by (metis One-nat-def Suc-le-mono Suc-pred eq-iff le0)
  have count χ' (Pos v) = 1
    using simplified-count[OF simp χ'ψ] pos by (metis One-nat-def Suc-le-mono Suc-pred eq-iff le0)
  obtain C where  $\chi C$ :  $\chi = C + \{\#Neg\ v\# \}$  and negC: Neg v  $\notin \# C$  and posC: Pos v  $\notin \# C$ 
  proof -
    assume a1:  $\bigwedge C. \llbracket \chi = C + \{\#Neg\ v\# \}; Neg\ v \notin \# C; Pos\ v \notin \# C \rrbracket \implies thesis$ 
    have f2:  $\bigwedge n. (0::nat) + n = n$ 
```

```

    by simp
  obtain mm :: 'v literal multiset  $\Rightarrow$  'v literal  $\Rightarrow$  'v literal multiset where
    f3:  $\{\#Neg\ v\#\} + mm\ \chi\ (Neg\ v) = \chi$ 
    by (metis (no-types)  $\langle count\ \chi\ (Neg\ v) = 1 \rangle$  add.commute multi-member-split
        zero-less-one)
  then have Pos v  $\notin\#$  mm  $\chi\ (Neg\ v)$ 
    using f2 by (metis (no-types) Posv  $\langle count\ \chi\ (Neg\ v) = 1 \rangle$  add.right-neutral
        add-left-cancel count-single count-union less-nat-zero-code)
  then show ?thesis
    using f3 a1 by (metis (no-types)  $\langle count\ \chi\ (Neg\ v) = 1 \rangle$  add.commute
        add.right-neutral add-left-cancel count-single count-union less-nat-zero-code)
qed
obtain C' where
   $\chi C'$ :  $\chi' = C' + \{\#Pos\ v\#$  and
  posC': Pos v  $\notin\#$  C' and
  negC': Neg v  $\notin\#$  C'
  by (metis (no-types, hide-lams) Negv  $\langle count\ \chi' (Pos\ v) = 1 \rangle$  add-diff-cancel-right'
      cancel-comm-monoid-add-class.diff-cancel count-diff count-single less-nat-zero-code
      mset-leD mset-le-add-left multi-member-split zero-less-one)

have totC: total-over-m I {C}
  using tot $\chi$  tot-over-m-remove[of I Pos v C] negC posC unfolding  $\chi C$ 
  by (metis total-over-m-sum uminus-Neg uminus-of-uminus-id)
have totC': total-over-m I {C'}
  using tot $\chi'$  total-over-m-sum tot-over-m-remove[of I Neg v C'] negC' posC'
  unfolding  $\chi C'$  by (metis total-over-m-sum uminus-Neg)
have  $\neg I \models C + C'$ 
  using  $\chi\ \chi'\ \chi C\ \chi C'$  by auto
then have part-I- $\psi'''$ : partial-interps Leaf I (fst  $\psi \cup \{C + C'\}$ )
  using totC totC'  $\neg I \models C + C'$  by (metis Un-insert-right insertI1
      partial-interps.simps(1) total-over-m-sum)
{
  assume  $(\{\#Pos\ v\# + C', \{\#Neg\ v\# + C\}) \notin snd\ \psi$ 
  then have inf'': inference  $\psi$  (fst  $\psi \cup \{C + C'\}$ , snd  $\psi \cup \{(\chi', \chi)\}$ )
    by (metis  $\chi'\psi\ \chi C\ \chi C'\ \chi\psi$  add.commute inference-step prod.collapse resolution)
  obtain N' where full: full simplify (fst  $\psi \cup \{C + C'\}$ ) N'
    by (metis finite-simplified-full-simp fst-conv inf'' inference-preserves-finite
        local.finite)
  have resolution  $\psi$  (N', snd  $\psi \cup \{(\chi', \chi)\}$ )
    using resolution.intros(2)[OF - simp full, of snd  $\psi$  snd  $\psi \cup \{(\chi', \chi)\}$ ] inf''
    by (metis surjective-pairing)
  moreover have partial-interps Leaf I N'
    using full-simplify-preserve-partial-tree[OF full part-I- $\psi'''$ ] .
  moreover have sem-tree-size Leaf < sem-tree-size xs unfolding xs by auto
  ultimately have ?case
    by (metis (no-types) prod.sel(1) rtrancpl.rtrancpl-into-rtrancpl rtrancpl.rtrancpl-refl)
}
moreover {
  assume a:  $(\{\#Pos\ v\# + C', \{\#Neg\ v\# + C\}) \in snd\ \psi$ 
  then have  $(\exists \chi \in fst\ \psi. (\forall I. total-over-m\ I\ \{C+C'\} \longrightarrow total-over-m\ I\ \{\chi\})$ 
     $\wedge (\forall I. total-over-m\ I\ \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models C' + C)) \vee tautology\ (C' + C)$ 
  proof -
    obtain p where p: Pos p  $\in\#$   $(\{\#Pos\ v\# + C') \wedge Neg\ p \in\#$   $(\{\#Neg\ v\# + C)$ 
       $\wedge ((\exists \chi \in fst\ \psi. (\forall I. total-over-m\ I\ \{(\{\#Pos\ v\# + C') - \{\#Pos\ p\# + (\{\#Neg\ v\# + C) - \{\#Neg\ p\#\}\} \longrightarrow total-over-m\ I\ \{\chi\}) \wedge (\forall I. total-over-m\ I\ \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models (\{\#Pos$ 

```



```

 $v\#\} + C') - \{\#Pos\ p\#\} + ((\{\#Neg\ v\#\} + C) - \{\#Neg\ p\#\})) \vee \text{tautology } ((\{\#Pos\ v\#\} + C') -$ 
 $\{\#Pos\ p\#\} + ((\{\#Neg\ v\#\} + C) - \{\#Neg\ p\#\}))$ 
using  $a$  by (blast intro: allE[OF a-u-i[unfolded subsumes-def Ball-def],
  of  $(\{\#Pos\ v\#\} + C', \{\#Neg\ v\#\} + C))$ )
{ assume  $p \neq v$ 
  then have  $Pos\ p \in\# C' \wedge Neg\ p \in\# C$  using  $p$  by force
  then have ?thesis by (metis add-gr-0 count-union tautology-Pos-Neg)
}
moreover {
  assume  $p = v$ 
  then have ?thesis using  $p$  by (metis add.commute add-diff-cancel-left')
}
ultimately show ?thesis by auto
qed
moreover {
assume  $\exists \chi \in fst\ \psi. (\forall I. total-over-m\ I\ \{C+C'\} \longrightarrow total-over-m\ I\ \{\chi\})$ 
 $\wedge (\forall I. total-over-m\ I\ \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models C' + C)$ 
then obtain  $\vartheta$  where
   $\vartheta: \vartheta \in fst\ \psi$  and
   $tot\text{-}\vartheta\text{-}CC': \forall I. total-over-m\ I\ \{C+C'\} \longrightarrow total-over-m\ I\ \{\vartheta\}$  and
   $\vartheta\text{-}inv: \forall I. total-over-m\ I\ \{\vartheta\} \longrightarrow I \models \vartheta \longrightarrow I \models C' + C$  by blast
have partial-interps Leaf I (fst ψ)
  using  $tot\text{-}\vartheta\text{-}CC'\ \vartheta\ \vartheta\text{-}inv\ totC\ totC' \hookrightarrow I \models C + C'$  total-over-m-sum by fastforce
moreover have sem-tree-size Leaf < sem-tree-size xs unfolding  $xs$  by auto
ultimately have ?case by blast
}
moreover {
assume  $tautCC': tautology\ (C' + C)$ 
have  $total-over-m\ I\ \{C'+C\}$  using  $totC\ totC'$  total-over-m-sum by auto
then have  $\neg tautology\ (C' + C)$ 
  using  $\hookrightarrow I \models C + C'$  unfolding  $add.commute[of\ C\ C']\ total-over-m-def$ 
unfolding tautology-def by auto
then have False using  $tautCC'$  unfolding tautology-def by auto
}
ultimately have ?case by auto
}
ultimately have ?case by auto
}
ultimately have ?case using part by (metis (no-types) sem-tree-size.simps(1))
}
moreover {
assume  $size-ag: sem-tree-size\ ag > 0$ 
have  $sem-tree-size\ ag < sem-tree-size\ xs$  unfolding  $xs$  by auto
moreover have partial-interps ag (I ∪ {Pos v}) (fst ψ)
and partad: partial-interps ad (I ∪ {Neg v}) (fst ψ)
  using part partial-interps.simps(2) unfolding  $xs$  by metis+
moreover
  have  $sem-tree-size\ ag < sem-tree-size\ xs \implies finite\ (fst\ \psi) \implies already-used-inv\ \psi$ 
 $\implies partial-interps\ ag\ (I \cup \{Pos\ v\})\ (fst\ \psi) \implies simplified\ (fst\ \psi)$ 
 $\implies \exists tree'\ \psi'. resolution^{**}\ \psi\ \psi' \wedge partial-interps\ tree'\ (I \cup \{Pos\ v\})\ (fst\ \psi')$ 
 $\wedge (sem-tree-size\ tree' < sem-tree-size\ ag \vee sem-tree-size\ ag = 0)$ 
  using IH[of ag I ∪ {Pos v}] by auto
ultimately obtain  $\psi' :: 'v\ state$  and  $tree' :: 'v\ sem-tree$  where
  inf: resolution^{**} ψ ψ'
and part: partial-interps tree' (I ∪ {Pos v}) (fst ψ')
}

```

```

    and size: sem-tree-size tree' < sem-tree-size ag ∨ sem-tree-size ag = 0
    using finite part rtranclp.rtrancl-refl a-u-i simp by blast

  have partial-interps ad (I ∪ {Neg v}) (fst ψ')
    using rtranclp-resolution-preserve-partial-tree inf partad by fast
  then have partial-interps (Node v tree' ad) I (fst ψ') using part by auto
  then have ?case using inf size size-ag part unfolding xs by fastforce
}
moreover {
  assume size-ad: sem-tree-size ad > 0
  have sem-tree-size ad < sem-tree-size xs unfolding xs by auto
  moreover
    have
      partag: partial-interps ag (I ∪ {Pos v}) (fst ψ) and
      partial-interps ad (I ∪ {Neg v}) (fst ψ)
      using part partial-interps.simps(2) unfolding xs by metis+
  moreover have sem-tree-size ad < sem-tree-size xs ⟶ finite (fst ψ) ⟶ already-used-inv ψ
    ⟶ ( partial-interps ad (I ∪ {Neg v}) (fst ψ) ⟶ simplified (fst ψ)
    ⟶ (∃ tree' ψ'. resolution** ψ ψ' ∧ partial-interps tree' (I ∪ {Neg v}) (fst ψ')
    ∧ (sem-tree-size tree' < sem-tree-size ad ∨ sem-tree-size ad = 0)))
    using IH by blast
  ultimately obtain ψ' :: 'v state and tree' :: 'v sem-tree where
    inf: resolution** ψ ψ'
    and part: partial-interps tree' (I ∪ {Neg v}) (fst ψ')
    and size: sem-tree-size tree' < sem-tree-size ad ∨ sem-tree-size ad = 0
    using finite part rtranclp.rtrancl-refl a-u-i simp by blast

  have partial-interps ag (I ∪ {Pos v}) (fst ψ')
    using rtranclp-resolution-preserve-partial-tree inf partag by fast
  then have partial-interps (Node v ag tree') I (fst ψ') using part by auto
  then have ?case using inf size size-ad unfolding xs by fastforce
}
ultimately have ?case by auto
}
ultimately show ?case by auto
qed

lemma resolution-completeness-inv:
  fixes ψ :: 'v :: linorder state
  assumes
    unsat: ¬satisfiable (fst ψ) and
    finite: finite (fst ψ) and
    a-u-v: already-used-inv ψ
  shows ∃ ψ'. (resolution** ψ ψ' ∧ {#} ∈ fst ψ')
proof -
  obtain tree where partial-interps tree {} (fst ψ)
  using partial-interps-build-sem-tree-atms assms by metis
  then show ?thesis
  using unsat finite a-u-v
  proof (induct tree arbitrary: ψ rule: sem-tree-size)
    case (bigger tree ψ) note H = this
    {
      fix χ
      assume tree: tree = Leaf
      obtain χ where χ: ¬ {} ⊨ χ and totχ: total-over-m {} {χ} and χψ: χ ∈ fst ψ
    }
  qed

```

```

    using H unfolding tree by auto
  moreover have  $\{\#\} = \chi$ 
    using H atms-empty-iff-empty tot $\chi$ 
    unfolding true-cls-def total-over-m-def total-over-set-def by fastforce
  moreover have resolution**  $\psi$   $\psi$  by auto
  ultimately have ?case by metis
}
moreover {
  fix v tree1 tree2
  assume tree: tree = Node v tree1 tree2
  obtain  $\psi_0$  where  $\psi_0$ : resolution**  $\psi$   $\psi_0$  and simp: simplified (fst  $\psi_0$ )
  proof -
    { assume simplified (fst  $\psi$ )
      moreover have resolution**  $\psi$   $\psi$  by auto
      ultimately have thesis using that by blast
    }
    moreover {
      assume  $\neg$ simplified (fst  $\psi$ )
      then have  $\exists \psi'. \text{full1 simplify } (\text{fst } \psi) \psi'$ 
        by (metis Nitpick.rtranclp-unfold bigger.prem(3) full1-def
          rtranclp-simplify-terminates)
      then obtain N where full1 simplify (fst  $\psi$ ) N by metis
      then have resolution  $\psi$  (N, snd  $\psi$ )
        using resolution.intros(1)[of fst  $\psi$  N snd  $\psi$ ] by auto
      moreover have simplified N
        using  $\langle \text{full1 simplify } (\text{fst } \psi) \text{ } N \rangle$  unfolding full1-def by blast
      ultimately have ?thesis using that by force
    }
    ultimately show ?thesis by auto
  qed
}

have p: partial-interps tree {} (fst  $\psi_0$ )
and uns: unsatisfiable (fst  $\psi_0$ )
and f: finite (fst  $\psi_0$ )
and a-u-v: already-used-inv  $\psi_0$ 
  using  $\psi_0$  bigger.prem(1) rtranclp-resolution-preserve-partial-tree apply blast
  using  $\psi_0$  bigger.prem(2) rtranclp-resolution-preserves-unsat apply blast
  using  $\psi_0$  bigger.prem(3) rtranclp-resolution-finite apply blast
  using rtranclp-resolution-already-used-inv[OF  $\psi_0$  bigger.prem(4)] by blast
obtain tree'  $\psi'$  where
  inf: resolution**  $\psi_0$   $\psi'$  and
  part': partial-interps tree' {} (fst  $\psi'$ ) and
  decrease: sem-tree-size tree' < sem-tree-size tree  $\vee$  sem-tree-size tree = 0
  using can-decrease-tree-size-resolution[OF f a-u-v p simp] unfolding tautology-def
  by meson
have s: sem-tree-size tree' < sem-tree-size tree using decrease unfolding tree by auto
have fin: finite (fst  $\psi'$ )
  using f inf rtranclp-resolution-finite by blast
have unsat: unsatisfiable (fst  $\psi'$ )
  using rtranclp-resolution-preserves-unsat inf uns by metis
have a-u-i': already-used-inv  $\psi'$ 
  using a-u-v inf rtranclp-resolution-already-used-inv[of  $\psi_0$   $\psi'$ ] by auto
have ?case
  using inf rtranclp-trans[of resolution] H(1)[OF s part' unsat fin a-u-i']  $\psi_0$  by blast

```

```

    }
    ultimately show ?case by (case-tac tree, auto)
  qed
qed

```

```

lemma resolution-preserves-already-used-inv:
  assumes resolution S S'
  and already-used-inv S
  shows already-used-inv S'
  using assms
  apply (induct rule: resolution.induct)
  apply (rule full1-simplify-already-used-inv; simp)
  apply (rule full-simplify-already-used-inv, simp)
  apply (rule inference-preserves-already-used-inv, simp)
  apply blast
done

```

```

lemma rtranclp-resolution-preserves-already-used-inv:
  assumes resolution** S S'
  and already-used-inv S
  shows already-used-inv S'
  using assms
  apply (induct rule: rtranclp-induct)
  apply simp
  using resolution-preserves-already-used-inv by fast

```

```

lemma resolution-completeness:
  fixes  $\psi :: 'v :: \text{linorder state}$ 
  assumes unsat:  $\neg \text{satisfiable (fst } \psi)$ 
  and finite:  $\text{finite (fst } \psi)$ 
  and snd  $\psi = \{\}$ 
  shows  $\exists \psi'. (\text{resolution** } \psi \psi' \wedge \{\#\} \in \text{fst } \psi')$ 
proof -
  have already-used-inv  $\psi$  unfolding assms by auto
  then show ?thesis using assms resolution-completeness-inv by blast
qed

```

```

lemma rtranclp-preserves-sat:
  assumes simplify** S S'
  and satisfiable S
  shows satisfiable S'
  using assms apply induction
  apply simp
  by (meson satisfiable-carac satisfiable-def simplify-preserves-un-sat-eq)

```

```

lemma resolution-preserves-sat:
  assumes resolution S S'
  and satisfiable (fst S)
  shows satisfiable (fst S')
  using assms apply (induction rule: resolution.induct)
  using rtranclp-preserves-sat tranclp-into-rtranclp unfolding full1-def apply fastforce
  by (metis fst-conv full-def inference-preserves-un-sat rtranclp-preserves-sat
    satisfiable-carac' satisfiable-def)

```

```

lemma rtranclp-resolution-preserves-sat:

```

```

assumes resolution**  $S \ S'$ 
and satisfiable (fst  $S$ )
shows satisfiable (fst  $S'$ )
using assms apply (induction rule: rtrancpl-induct)
apply simp
using resolution-preserves-sat by blast

lemma resolution-soundness:
  fixes  $\psi :: 'v :: \text{linorder state}$ 
  assumes resolution**  $\psi \ \psi'$  and  $\{\#\} \in \text{fst } \psi'$ 
  shows unsatisfiable (fst  $\psi$ )
  using assms by (meson rtrancpl-resolution-preserves-sat satisfiable-def true-cls-empty
    true-cls-def)

lemma resolution-soundness-and-completeness:
  fixes  $\psi :: 'v :: \text{linorder state}$ 
  assumes finite: finite (fst  $\psi$ )
  and snd: snd  $\psi = \{\}$ 
  shows  $(\exists \psi'. (\text{resolution}^{**} \ \psi \ \psi' \wedge \{\#\} \in \text{fst } \psi')) \longleftrightarrow \text{unsatisfiable } (\text{fst } \psi)$ 
  using assms resolution-completeness resolution-soundness by metis

lemma simplified-falsity:
  assumes simp: simplified  $\psi$ 
  and  $\{\#\} \in \psi$ 
  shows  $\psi = \{\{\#\}\}$ 
proof (rule ccontr)
  assume  $H: \neg \text{thesis}$ 
  then obtain  $\chi$  where  $\chi \in \psi$  and  $\chi \neq \{\#\}$  using assms(2) by blast
  then have  $\{\#\} \subsetneq \chi$  by (simp add: mset-less-empty-nonempty)
  then have simplify  $\psi$   $(\psi - \{\chi\})$ 
  using simplify.subsumption[OF assms(2)  $\langle \{\#\} \subsetneq \chi \rangle \langle \chi \in \psi \rangle$ ] by blast
  then show False using simp by blast
qed

lemma simplify-falsity-in-preserved:
  assumes simplify  $\chi s \ \chi s'$ 
  and  $\{\#\} \in \chi s$ 
  shows  $\{\#\} \in \chi s'$ 
  using assms
  by induction auto

lemma rtrancpl-simplify-falsity-in-preserved:
  assumes simplify**  $\chi s \ \chi s'$ 
  and  $\{\#\} \in \chi s$ 
  shows  $\{\#\} \in \chi s'$ 
  using assms
  by induction (auto intro: simplify-falsity-in-preserved)

lemma resolution-falsity-get-falsity-alone:
  assumes finite (fst  $\psi$ )
  shows  $(\exists \psi'. (\text{resolution}^{**} \ \psi \ \psi' \wedge \{\#\} \in \text{fst } \psi')) \longleftrightarrow (\exists a-u-v. \text{resolution}^{**} \ \psi \ (\{\{\#\}\}, a-u-v))$ 
  (is  $?A \longleftrightarrow ?B$ )
proof
  assume  $?B$ 

```

```

    then show ?A by auto
next
assume ?A
then obtain  $\chi s$  a-u-v where  $\chi s$ : resolution**  $\psi$  ( $\chi s$ , a-u-v) and  $F$ :  $\{\#\} \in \chi s$  by auto
{ assume simplified  $\chi s$ 
  then have ?B using simplified-falsity[OF - F]  $\chi s$  by blast
}
moreover {
  assume  $\neg$  simplified  $\chi s$ 
  then obtain  $\chi s'$  where full1 simplify  $\chi s$   $\chi s'$ 
    by (metis  $\chi s$  assms finite-simplified-full1-simp fst-conv rtranclp-resolution-finite)
  then have  $\{\#\} \in \chi s'$ 
    unfolding full1-def by (meson F rtranclp-simplify-falsity-in-preserved
      tranclp-into-rtranclp)
  then have ?B
    by (metis  $\chi s$  (full1 simplify  $\chi s$   $\chi s'$ ) fst-conv full1-simp resolution-always-simplified
      rtranclp.rtrancl-into-rtrancl simplified-falsity)
}
ultimately show ?B by blast
qed

lemma resolution-soundness-and-completeness':
  fixes  $\psi :: 'v :: \text{linorder}$  state
  assumes
    finite: finite (fst  $\psi$ ) and
    snd: snd  $\psi = \{\}$ 
  shows  $(\exists a-u-v. (\text{resolution}^{**} \psi (\{\#\}, a-u-v))) \longleftrightarrow \text{unsatisfiable} (\text{fst } \psi)$ 
    using assms resolution-completeness resolution-soundness resolution-falsity-get-falsity-alone
    by metis

end

theory Partial-Annotated-Clausal-Logic
imports Partial-Clausal-Logic

begin

```

13 Partial Clausal Logic

We here define marked literals (that will be used in both DPLL and CDCL) and the entailment corresponding to it.

13.1 Marked Literals

13.1.1 Definition

```

datatype ('v, 'wl, 'mark) marked-lit =
  is-marked: Marked (lit-of: 'v literal) (level-of: 'wl) |
  is-proped: Propagated (lit-of: 'v literal) (mark-of: 'mark)

```

```

lemma marked-lit-list-induct[case-names nil marked proped]:
  assumes  $P \ []$  and
     $\bigwedge L \ l \ xs. P \ xs \implies P \ (\text{Marked } L \ l \ \# \ xs)$  and
     $\bigwedge L \ m \ xs. P \ xs \implies P \ (\text{Propagated } L \ m \ \# \ xs)$ 
  shows  $P \ xs$ 

```

using *assms* **apply** (*induction xs, simp*)
by (*case-tac a*) *auto*

lemma *is-marked-ex-Marked*:
is-marked L $\implies \exists K \text{ lvl. } L = \text{Marked } K \text{ lvl}$
by (*cases L*) *auto*

type-synonym (*'v, 'l, 'm*) *marked-lits* = (*'v, 'l, 'm*) *marked-lit list*

definition *lits-of* :: (*'a, 'b, 'c*) *marked-lit list* \Rightarrow *'a literal set* **where**
lits-of Ls = *lit-of* ' (*set Ls*)

lemma *lits-of-empty*[*simp*]:
lits-of [] = {} **unfolding** *lits-of-def* **by** *auto*

lemma *lits-of-cons*[*simp*]:
lits-of (*L # Ls*) = *insert* (*lit-of L*) (*lits-of Ls*)
unfolding *lits-of-def* **by** *auto*

lemma *lits-of-append*[*simp*]:
lits-of (*l @ l'*) = *lits-of l* \cup *lits-of l'*
unfolding *lits-of-def* **by** *auto*

lemma *finite-lits-of-def*[*simp*]: *finite* (*lits-of L*)
unfolding *lits-of-def* **by** *auto*

lemma *lits-of-rev*[*simp*]: *lits-of* (*rev M*) = *lits-of M*
unfolding *lits-of-def* **by** *auto*

lemma *set-map-lit-of-lits-of*[*simp*]:
set (*map lit-of T*) = *lits-of T*
unfolding *lits-of-def* **by** *auto*

lemma *atms-of-ms-lambda-lit-of-is-atm-of-lit-of*[*simp*]:
atms-of-ms (($\lambda a. \{\# \text{lit-of } a \# \}$) ' *set M'*) = *atm-of* ' *lits-of M'*
unfolding *atms-of-ms-def lits-of-def* **by** *auto*

lemma *lits-of-empty-is-empty*[*iff*]:
lits-of M = {} $\longleftrightarrow M$ = []
by (*induct M*) *auto*

13.1.2 Entailment

definition *true-annot* :: (*'a, 'l, 'm*) *marked-lits* \Rightarrow *'a clause* \Rightarrow *bool* (**infix** \models_a 49) **where**
I $\models_a C \longleftrightarrow (\text{lits-of } I) \models C$

definition *true-annots* :: (*'a, 'l, 'm*) *marked-lits* \Rightarrow *'a clauses* \Rightarrow *bool* (**infix** \models_{as} 49) **where**
I $\models_{as} CC \longleftrightarrow (\forall C \in CC. I \models_a C)$

lemma *true-annot-empty-model*[*simp*]:
 $\neg [] \models_a \psi$
unfolding *true-annot-def true-cl-def* **by** *simp*

lemma *true-annot-empty*[*simp*]:
 $\neg I \models_a \{\#\}$
unfolding *true-annot-def true-cl-def* **by** *simp*

lemma *empty-true-annots-def*[*iff*]:
 $\square \models_{as} \psi \longleftrightarrow \psi = \{\}$
unfolding *true-annots-def* **by** *auto*

lemma *true-annots-empty*[*simp*]:
 $I \models_{as} \{\}$
unfolding *true-annots-def* **by** *auto*

lemma *true-annots-single-true-annot*[*iff*]:
 $I \models_{as} \{C\} \longleftrightarrow I \models_a C$
unfolding *true-annots-def* **by** *auto*

lemma *true-annot-insert-l*[*simp*]:
 $M \models_a A \implies L \# M \models_a A$
unfolding *true-annot-def* **by** *auto*

lemma *true-annots-insert-l* [*simp*]:
 $M \models_{as} A \implies L \# M \models_{as} A$
unfolding *true-annots-def* **by** *auto*

lemma *true-annots-union*[*iff*]:
 $M \models_{as} A \cup B \longleftrightarrow (M \models_{as} A \wedge M \models_{as} B)$
unfolding *true-annots-def* **by** *auto*

lemma *true-annots-insert*[*iff*]:
 $M \models_{as} \text{insert } a \ A \longleftrightarrow (M \models_a a \wedge M \models_{as} A)$
unfolding *true-annots-def* **by** *auto*

Link between \models_{as} and \models_s :

lemma *true-annots-true-cls*:
 $I \models_{as} CC \longleftrightarrow (\text{lits-of } I) \models_s CC$
unfolding *true-annots-def* *Ball-def* *true-annot-def* *true-clss-def* **by** *auto*

lemma *in-lit-of-true-annot*:
 $a \in \text{lits-of } M \longleftrightarrow M \models_a \{\#a\# \}$
unfolding *true-annot-def* *lits-of-def* **by** *auto*

lemma *true-annot-lit-of-notin-skip*:
 $L \# M \models_a A \implies \text{lit-of } L \notin \# A \implies M \models_a A$
unfolding *true-annot-def* *true-cls-def* **by** *auto*

lemma *true-clss-singleton-lit-of-implies-incl*:
 $I \models_s (\lambda a. \{\# \text{lit-of } a \# \}) \text{ 'set MLs } \implies \text{lits-of MLs} \subseteq I$
unfolding *true-clss-def* *lits-of-def* **by** *auto*

lemma *true-annot-true-clss-cls*:
 $MLs \models_a \psi \implies \text{set } (\text{map } (\lambda a. \{\# \text{lit-of } a \# \}) \ MLs) \models_p \psi$
unfolding *true-annot-def* *true-clss-cls-def* *true-cls-def*
by (*auto dest: true-clss-singleton-lit-of-implies-incl*)

lemma *true-annots-true-clss-cls*:
 $MLs \models_{as} \psi \implies \text{set } (\text{map } (\lambda a. \{\# \text{lit-of } a \# \}) \ MLs) \models_{ps} \psi$
by (*auto*)

dest: true-clss-singleton-lit-of-implies-incl
simp add: true-clss-def true-annot-def true-annot-def lits-of-def true-clss-def
true-clss-clss-def)

lemma true-annots-marked-true-clss[iff]:

map ($\lambda M. \text{Marked } M \ a$) $M \models_{as} N \longleftrightarrow \text{set } M \models_s N$

proof –

have *: *lits-of* (*map* ($\lambda M. \text{Marked } M \ a$) M) = *set* M **unfolding** *lits-of-def* **by** *force*

show ?thesis **by** (*simp add*: true-annots-true-clss *)

qed

lemma true-annot-singleton[iff]: $M \models_a \{\#L\# \} \longleftrightarrow L \in \text{lits-of } M$

unfolding true-annot-def *lits-of-def* **by** *auto*

lemma true-annots-true-clss-clss:

$A \models_{as} \Psi \implies (\lambda a. \{\# \text{lit-of } a \#\}) \text{ 'set } A \models_{ps} \Psi$

unfolding true-clss-clss-def true-annots-def true-clss-def

by (*auto*

dest!: true-clss-singleton-lit-of-implies-incl

simp add: *lits-of-def* true-annot-def true-clss-def)

lemma true-annot-commute:

$M @ M' \models_a D \longleftrightarrow M' @ M \models_a D$

unfolding true-annot-def **by** (*simp add*: Un-commute)

lemma true-annots-commute:

$M @ M' \models_{as} D \longleftrightarrow M' @ M \models_{as} D$

unfolding true-annots-def **by** (*auto simp add*: true-annot-commute)

lemma true-annot-mono[dest]:

$\text{set } I \subseteq \text{set } I' \implies I \models_a N \implies I' \models_a N$

using true-clss-mono-set-mset-l **unfolding** true-annot-def *lits-of-def*

by (*metis* (*no-types*) Un-commute Un-upper1 image-Un sup.orderE)

lemma true-annots-mono:

$\text{set } I \subseteq \text{set } I' \implies I \models_{as} N \implies I' \models_{as} N$

unfolding true-annots-def **by** *auto*

13.1.3 Defined and undefined literals

definition *defined-lit* :: ('a, 'l, 'm) marked-lit list \Rightarrow 'a literal \Rightarrow bool

where

defined-lit $I \ L \longleftrightarrow (\exists l. \text{Marked } L \ l \in \text{set } I) \vee (\exists P. \text{Propagated } L \ P \in \text{set } I)$

$\vee (\exists l. \text{Marked } (-L) \ l \in \text{set } I) \vee (\exists P. \text{Propagated } (-L) \ P \in \text{set } I)$

abbreviation *undefined-lit* :: ('a, 'l, 'm) marked-lit list \Rightarrow 'a literal \Rightarrow bool

where *undefined-lit* $I \ L \equiv \neg \text{defined-lit } I \ L$

lemma *defined-lit-rev*[simp]:

defined-lit (*rev* M) $L \longleftrightarrow \text{defined-lit } M \ L$

unfolding *defined-lit-def* **by** *auto*

lemma *atm-imp-marked-or-proped*:

assumes $x \in \text{set } I$

shows

$(\exists l. \text{Marked } (- \text{lit-of } x) \ l \in \text{set } I)$

$\vee (\exists l. \text{Marked } (\text{lit-of } x) \ l \in \text{set } I)$
 $\vee (\exists l. \text{Propagated } (\neg \text{lit-of } x) \ l \in \text{set } I)$
 $\vee (\exists l. \text{Propagated } (\text{lit-of } x) \ l \in \text{set } I)$
using *assms marked-lit.exhaust-sel* **by** *metis*

lemma *literal-is-lit-of-marked*:

assumes $L = \text{lit-of } x$
shows $(\exists l. x = \text{Marked } L \ l) \vee (\exists l'. x = \text{Propagated } L \ l')$
using *assms* **by** (*case-tac x*) *auto*

lemma *true-annot-iff-marked-or-true-lit*:

$\text{defined-lit } I \ L \longleftrightarrow ((\text{lits-of } I) \models L \vee (\text{lits-of } I) \models \neg L)$
unfolding *defined-lit-def* **by** (*auto simp add: lits-of-def rev-image-eqI*
dest!: literal-is-lit-of-marked)

lemma *consistent-interp* $(\text{lits-of } I) \Longrightarrow I \models_{\text{as}} N \Longrightarrow \text{satisfiable } N$
by (*simp add: true-annots-true-cls*)

lemma *defined-lit-map*:

$\text{defined-lit } Ls \ L \longleftrightarrow \text{atm-of } L \in (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ 'set } Ls$
unfolding *defined-lit-def* **apply** (*rule iffI*)
using *image-iff* **apply** *fastforce*
by (*fastforce simp add: atm-of-eq-atm-of dest: atm-imp-marked-or-proped*)

lemma *defined-lit-uminus[iff]*:

$\text{defined-lit } I \ (\neg L) \longleftrightarrow \text{defined-lit } I \ L$
unfolding *defined-lit-def* **by** *auto*

lemma *Marked-Propagated-in-iff-in-lits-of*:

$\text{defined-lit } I \ L \longleftrightarrow (L \in \text{lits-of } I \vee \neg L \in \text{lits-of } I)$
unfolding *lits-of-def* *defined-lit-def*
by (*auto simp add: rev-image-eqI*) (*case-tac x, auto*)+

lemma *consistent-add-undefined-lit-consistent[simp]*:

assumes
 $\text{consistent-interp } (\text{lits-of } Ls)$ **and**
 $\text{undefined-lit } Ls \ L$
shows $\text{consistent-interp } (\text{insert } L \ (\text{lits-of } Ls))$
using *assms* **unfolding** *consistent-interp-def* **by** (*auto simp: Marked-Propagated-in-iff-in-lits-of*)

lemma *decided-empty[simp]*:

$\neg \text{defined-lit } [] \ L$
unfolding *defined-lit-def* **by** *simp*

13.2 Backtracking

fun *backtrack-split* :: $('v, 'l, 'm) \text{ marked-lits}$

$\Rightarrow ('v, 'l, 'm) \text{ marked-lits} \times ('v, 'l, 'm) \text{ marked-lits}$ **where**

backtrack-split $[] = ([], [])$ |

backtrack-split $(\text{Propagated } L \ P \ \# \ \text{mlits}) = \text{apfst } ((\text{op } \#) \ (\text{Propagated } L \ P)) \ (\text{backtrack-split } \text{mlits})$ |

backtrack-split $(\text{Marked } L \ l \ \# \ \text{mlits}) = ([], \text{Marked } L \ l \ \# \ \text{mlits})$

lemma *backtrack-split-fst-not-marked*: $a \in \text{set } (\text{fst } (\text{backtrack-split } l)) \Longrightarrow \neg \text{is-marked } a$
by (*induct l rule: marked-lit-list-induct*) *auto*

lemma *backtrack-split-snd-hd-marked*:

snd (backtrack-split l) ≠ [] ⇒ is-marked (hd (snd (backtrack-split l)))
by (induct l rule: marked-lit-list-induct) auto

lemma *backtrack-split-list-eq[simp]*:
fst (backtrack-split l) @ (snd (backtrack-split l)) = l
by (induct l rule: marked-lit-list-induct) auto

lemma *backtrack-snd-empty-not-marked*:
backtrack-split M = (M'', []) ⇒ ∀ l ∈ set M. ¬ is-marked l
by (metis append-Nil2 backtrack-split-fst-not-marked backtrack-split-list-eq snd-conv)

lemma *backtrack-split-some-is-marked-then-snd-has-hd*:
 $\exists l \in \text{set } M. \text{is-marked } l \Rightarrow \exists M' L' M''. \text{backtrack-split } M = (M'', L' \# M')$
by (metis backtrack-snd-empty-not-marked list.exhaust prod.collapse)

Another characterisation of the result of *backtrack-split*. This view allows some simpler proofs, since *takeWhile* and *dropWhile* are highly automated:

lemma *backtrack-split-takeWhile-dropWhile*:
backtrack-split M = (takeWhile (Not o is-marked) M, dropWhile (Not o is-marked) M)
proof (induct M)
 case Nil show ?case **by** simp
next
 case (Cons L M) **thus** ?case **by** (cases L) auto
qed

13.3 Decomposition with respect to the marked literals

The pattern *get-all-marked-decomposition* [] = [([], [])] is necessary otherwise, we can call the *hd* function in the other pattern.

fun *get-all-marked-decomposition* :: ('a, 'l, 'm) marked-lits
 ⇒ (('a, 'l, 'm) marked-lits × ('a, 'l, 'm) marked-lits) list **where**
get-all-marked-decomposition (Marked L l # Ls) =
 (Marked L l # Ls, []) # *get-all-marked-decomposition* Ls |
get-all-marked-decomposition (Propagated L P # Ls) =
 (apsnd ((op #) (Propagated L P)) (hd (*get-all-marked-decomposition* Ls)))
 # tl (*get-all-marked-decomposition* Ls) |
get-all-marked-decomposition [] = [([], [])]

value *get-all-marked-decomposition* [Propagated A5 B5, Marked C4 D4, Propagated A3 B3,
 Propagated A2 B2, Marked C1 D1, Propagated A0 B0]

lemma *get-all-marked-decomposition-never-empty[iff]*:
get-all-marked-decomposition M = [] ⇔ False
by (induct M, simp) (case-tac a, auto)

lemma *get-all-marked-decomposition-never-empty-sym[iff]*:
 [] = *get-all-marked-decomposition M* ⇔ False
using *get-all-marked-decomposition-never-empty[of M]* **by** presburger

lemma *get-all-marked-decomposition-decomp*:
hd (get-all-marked-decomposition S) = (a, c) ⇒ S = c @ a
proof (induct S arbitrary: a c)
 case Nil
thus ?case **by** simp

```

next
  case (Cons x A)
  thus ?case by (cases x; cases hd (get-all-marked-decomposition A)) auto
qed

lemma get-all-marked-decomposition-backtrack-split:
  backtrack-split S = (M, M')  $\longleftrightarrow$  hd (get-all-marked-decomposition S) = (M', M)
proof (induction S arbitrary: M M')
  case Nil
  thus ?case by auto
next
  case (Cons a S)
  thus ?case using backtrack-split-takeWhile-dropWhile by (cases a) force+
qed

lemma get-all-marked-decomposition-nil-backtrack-split-snd-nil:
  get-all-marked-decomposition S = [([], A)]  $\implies$  snd (backtrack-split S) = []
  by (simp add: get-all-marked-decomposition-backtrack-split sndI)

lemma get-all-marked-decomposition-length-1-fst-empty-or-length-1:
  assumes get-all-marked-decomposition M = (a, b) # []
  shows a = []  $\vee$  (length a = 1  $\wedge$  is-marked (hd a)  $\wedge$  hd a  $\in$  set M)
  using assms
proof (induct M arbitrary: a b)
  case Nil thus ?case by simp
next
  case (Cons m M)
  show ?case
  proof (cases m)
    case (Marked l mark)
    thus ?thesis using Cons by simp
  next
    case (Propagated l mark)
    thus ?thesis using Cons by (cases get-all-marked-decomposition M) force+
  qed
qed

lemma get-all-marked-decomposition-fst-empty-or-hd-in-M:
  assumes get-all-marked-decomposition M = (a, b) # l
  shows a = []  $\vee$  (is-marked (hd a)  $\wedge$  hd a  $\in$  set M)
  using assms apply (induct M arbitrary: a b rule: marked-lit-list-induct)
  apply auto[2]
  by (metis UnCI backtrack-split-snd-hd-marked get-all-marked-decomposition-backtrack-split
    get-all-marked-decomposition-decomp hd-in-set list.sel(1) set-append snd-conv)

lemma get-all-marked-decomposition-snd-not-marked:
  assumes (a, b)  $\in$  set (get-all-marked-decomposition M)
  and L  $\in$  set b
  shows  $\neg$ is-marked L
  using assms apply (induct M arbitrary: a b rule: marked-lit-list-induct, simp)
  by (case-tac get-all-marked-decomposition xs; fastforce)+

lemma tl-get-all-marked-decomposition-skip-some:
  assumes x  $\in$  set (tl (get-all-marked-decomposition M1))
  shows x  $\in$  set (tl (get-all-marked-decomposition (M0 @ M1)))

```

```

using assms
by (induct M0 rule: marked-lit-list-induct)
   (auto simp add: list.set-sel(2))

lemma hd-get-all-marked-decomposition-skip-some:
  assumes (x, y) = hd (get-all-marked-decomposition M1)
  shows (x, y) ∈ set (get-all-marked-decomposition (M0 @ Marked K i # M1))
  using assms
proof (induct M0)
  case Nil
  thus ?case by auto
next
  case (Cons L M0)
  hence xy: (x, y) ∈ set (get-all-marked-decomposition (M0 @ Marked K i # M1)) by blast
  show ?case
  proof (cases L)
    case (Marked l m)
    thus ?thesis using xy by auto
  next
    case (Propagated l m)
    thus ?thesis
      using xy Cons.prem by
      by (cases get-all-marked-decomposition (M0 @ Marked K i # M1))
         (auto dest!: get-all-marked-decomposition-decomp
            arg-cong[get-all-marked-decomposition - - hd])
  qed
qed

lemma get-all-marked-decomposition-snd-union:
  set M =  $\bigcup$  (set 'snd ' set (get-all-marked-decomposition M))  $\cup$  {L | L. is-marked L  $\wedge$  L ∈ set M}
  (is ?M M = ?U M  $\cup$  ?Ls M)
proof (induct M arbitrary:)
  case Nil
  thus ?case by simp
next
  case (Cons L M)
  show ?case
  proof (cases L)
    case (Marked a l) note L = this
    hence L ∈ ?Ls (L#M) by auto
    moreover have ?U (L#M) = ?U M unfolding L by auto
    moreover have ?M M = ?U M  $\cup$  ?Ls M using Cons.hyps by auto
    ultimately show ?thesis by auto
  next
    case (Propagated a P)
    thus ?thesis using Cons.hyps by (cases (get-all-marked-decomposition M)) auto
  qed
qed

lemma in-get-all-marked-decomposition-in-get-all-marked-decomposition-prepend:
  (a, b) ∈ set (get-all-marked-decomposition M')  $\implies$ 
   $\exists b'. (a, b' @ b) \in \text{set (get-all-marked-decomposition (M @ M'))}$ 
  apply (induction M rule: marked-lit-list-induct)
  apply (metis append-Nil)
  apply auto[]

```

```

by (case-tac get-all-marked-decomposition (xs @ M')) auto

lemma get-all-marked-decomposition-remove-unmarked-length:
  assumes  $\forall l \in \text{set } M'. \neg \text{is-marked } l$ 
  shows  $\text{length } (\text{get-all-marked-decomposition } (M' @ M''))$ 
    =  $\text{length } (\text{get-all-marked-decomposition } M'')$ 
  using assms by (induct M' arbitrary: M'' rule: marked-lit-list-induct) auto

lemma get-all-marked-decomposition-not-is-marked-length:
  assumes  $\forall l \in \text{set } M'. \neg \text{is-marked } l$ 
  shows  $1 + \text{length } (\text{get-all-marked-decomposition } (\text{Propagated } (-L) P \# M))$ 
    =  $\text{length } (\text{get-all-marked-decomposition } (M' @ \text{Marked } L l \# M))$ 
  using assms get-all-marked-decomposition-remove-unmarked-length by fastforce

lemma get-all-marked-decomposition-last-choice:
  assumes  $\text{tl } (\text{get-all-marked-decomposition } (M' @ \text{Marked } L l \# M)) \neq []$ 
  and  $\forall l \in \text{set } M'. \neg \text{is-marked } l$ 
  and  $\text{hd } (\text{tl } (\text{get-all-marked-decomposition } (M' @ \text{Marked } L l \# M))) = (M0', M0)$ 
  shows  $\text{hd } (\text{get-all-marked-decomposition } (\text{Propagated } (-L) P \# M)) = (M0', \text{Propagated } (-L) P \# M0)$ 
  using assms by (induct M' rule: marked-lit-list-induct) auto

lemma get-all-marked-decomposition-except-last-choice-equal:
  assumes  $\forall l \in \text{set } M'. \neg \text{is-marked } l$ 
  shows  $\text{tl } (\text{get-all-marked-decomposition } (\text{Propagated } (-L) P \# M))$ 
    =  $\text{tl } (\text{tl } (\text{get-all-marked-decomposition } (M' @ \text{Marked } L l \# M)))$ 
  using assms by (induct M' rule: marked-lit-list-induct) auto

lemma get-all-marked-decomposition-hd-hd:
  assumes  $\text{get-all-marked-decomposition } Ls = (M, C) \# (M0, M0') \# l$ 
  shows  $\text{tl } M = M0' @ M0 \wedge \text{is-marked } (\text{hd } M)$ 
  using assms
proof (induct Ls arbitrary: M C M0 M0' l)
  case Nil
  thus ?case by simp
next
  case (Cons a Ls M C M0 M0' l)
  note IH = this(1) and g = this(2)
  { fix L level
    assume a:  $a = \text{Marked } L \text{ level}$ 
    have  $Ls = M0' @ M0$ 
    using g a by (force intro: get-all-marked-decomposition-decomp)
    hence  $\text{tl } M = M0' @ M0 \wedge \text{is-marked } (\text{hd } M)$  using g a by auto
  }
  moreover {
    fix L P
    assume a:  $a = \text{Propagated } L P$ 
    have  $\text{tl } M = M0' @ M0 \wedge \text{is-marked } (\text{hd } M)$ 
    using IH Cons.premis unfolding a by (cases get-all-marked-decomposition Ls) auto
  }
  ultimately show ?case by (cases a) auto
qed

lemma get-all-marked-decomposition-exists-prepend[dest]:
  assumes  $(a, b) \in \text{set } (\text{get-all-marked-decomposition } M)$ 
  shows  $\exists c. M = c @ b @ a$ 

```

```

using assms apply (induct M rule: marked-lit-list-induct)
apply simp
by (case-tac get-all-marked-decomposition xs;
    auto dest!: arg-cong[of get-all-marked-decomposition - - hd]
    get-all-marked-decomposition-decomp) +

lemma get-all-marked-decomposition-incl:
  assumes  $(a, b) \in \text{set } (\text{get-all-marked-decomposition } M)$ 
  shows  $\text{set } b \subseteq \text{set } M$  and  $\text{set } a \subseteq \text{set } M$ 
  using assms get-all-marked-decomposition-exists-prepend by fastforce +

lemma get-all-marked-decomposition-exists-prepend':
  assumes  $(a, b) \in \text{set } (\text{get-all-marked-decomposition } M)$ 
  obtains c where  $M = c @ b @ a$ 
  using assms apply (induct M rule: marked-lit-list-induct)
  apply auto[1]
  by (case-tac hd (get-all-marked-decomposition xs),
    auto dest!: get-all-marked-decomposition-decomp simp add: list.set-sel(2)) +

lemma union-in-get-all-marked-decomposition-is-subset:
  assumes  $(a, b) \in \text{set } (\text{get-all-marked-decomposition } M)$ 
  shows  $\text{set } a \cup \text{set } b \subseteq \text{set } M$ 
  using assms by force

definition all-decomposition-implies :: 'a literal multiset set
   $\Rightarrow ((\text{'a}, \text{'l}, \text{'m}) \text{ marked-lit list} \times (\text{'a}, \text{'l}, \text{'m}) \text{ marked-lit list}) \text{ list} \Rightarrow \text{bool})$  where
  all-decomposition-implies N S
   $\longleftrightarrow (\forall (Ls, \text{seen}) \in \text{set } S. (\lambda a. \{\# \text{lit-of } a \# \}) \text{ ' set } Ls \cup N \models_{ps} (\lambda a. \{\# \text{lit-of } a \# \}) \text{ ' set seen})$ 

lemma all-decomposition-implies-empty[iff]:
  all-decomposition-implies N [] unfolding all-decomposition-implies-def by auto

lemma all-decomposition-implies-single[iff]:
  all-decomposition-implies N [(Ls, seen)]
   $\longleftrightarrow (\lambda a. \{\# \text{lit-of } a \# \}) \text{ ' set } Ls \cup N \models_{ps} (\lambda a. \{\# \text{lit-of } a \# \}) \text{ ' set seen}$ 
  unfolding all-decomposition-implies-def by auto

lemma all-decomposition-implies-append[iff]:
  all-decomposition-implies N (S @ S')
   $\longleftrightarrow (\text{all-decomposition-implies } N \text{ } S \wedge \text{all-decomposition-implies } N \text{ } S')$ 
  unfolding all-decomposition-implies-def by auto

lemma all-decomposition-implies-cons-pair[iff]:
  all-decomposition-implies N ((Ls, seen) # S')
   $\longleftrightarrow (\text{all-decomposition-implies } N \text{ } [(Ls, \text{seen})] \wedge \text{all-decomposition-implies } N \text{ } S')$ 
  unfolding all-decomposition-implies-def by auto

lemma all-decomposition-implies-cons-single[iff]:
  all-decomposition-implies N (l # S')  $\longleftrightarrow$ 
   $((\lambda a. \{\# \text{lit-of } a \# \}) \text{ ' set } (\text{fst } l) \cup N \models_{ps} (\lambda a. \{\# \text{lit-of } a \# \}) \text{ ' set } (\text{snd } l) \wedge$ 
  all-decomposition-implies N S')
  unfolding all-decomposition-implies-def by auto

lemma all-decomposition-implies-trail-is-implied:

```

```

assumes all-decomposition-implies N (get-all-marked-decomposition M)
shows  $N \cup \{\{\#lit\text{-of } L\# \mid L. \text{is-marked } L \wedge L \in \text{set } M\}\}$ 
 $\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' } \bigcup (\text{set ' snd ' set (get-all-marked-decomposition M))$ 
using assms
proof (induct length (get-all-marked-decomposition M) arbitrary: M)
  case 0
  thus ?case by auto
next
case (Suc n) note IH = this(1) and length = this(2)
{
  assume length (get-all-marked-decomposition M) ≤ 1
  then obtain a b where g: get-all-marked-decomposition M = (a, b) # []
  by (case-tac get-all-marked-decomposition M) auto
  moreover {
    assume a = []
    hence ?case using Suc.prem1 g by auto
  }
  moreover {
    assume l: length a = 1 and m: is-marked (hd a) and hd: hd a ∈ set M
    hence  $(\lambda a. \{\#lit\text{-of } a\# \}) (\text{hd } a) \in \{\{\#lit\text{-of } L\# \mid L. \text{is-marked } L \wedge L \in \text{set } M\}\}$  by auto
    hence H: (λa. {#lit-of a#}) ' set a ∪ N ⊆ N ∪ {#lit-of L#} | L. is-marked L ∧ L ∈ set M
    using l by (cases a) auto
    have f1: (λm. {#lit-of m#}) ' set a ∪ N ⊆ N ∪ {#lit-of m#} ' set b
    using Suc.prem1 unfolding all-decomposition-implies-def g by simp
    have ?case
    unfolding g apply (rule true-clss-clss-subset) using f1 H by auto
  }
  ultimately have ?case using get-all-marked-decomposition-length-1-fst-empty-or-length-1 by blast
}
moreover {
  assume length (get-all-marked-decomposition M) > 1
  then obtain Ls0 seen0 M' where
    Ls0: get-all-marked-decomposition M = (Ls0, seen0) # get-all-marked-decomposition M' and
    length': length (get-all-marked-decomposition M') = n and
    M'-in-M: set M' ⊆ set M
  using length apply (induct M)
  apply simp
  by (case-tac a, case-tac hd (get-all-marked-decomposition M))
    (auto simp add: subset-insertI2)
  {
    assume n = 0
    hence get-all-marked-decomposition M' = [] using length' by auto
    hence ?case using Suc.prem1 unfolding all-decomposition-implies-def Ls0 by auto
  }
  moreover {
    assume n: n > 0
    then obtain Ls1 seen1 l where Ls1: get-all-marked-decomposition M' = (Ls1, seen1) # l
    using length' by (induct M', simp) (case-tac a, auto)

    have all-decomposition-implies N (get-all-marked-decomposition M')
    using Suc.prem1 unfolding Ls0 all-decomposition-implies-def by auto
    hence N: N ∪ {#lit-of L#} | L. is-marked L ∧ L ∈ set M'
     $\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' } \bigcup (\text{set ' snd ' set (get-all-marked-decomposition M')})$ 
    using IH length' by auto
  }
}

```



```

have l:  $N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M'\}$ 
   $\subseteq N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$ 
  using  $M'\text{-in-}M$  by auto
hence  $\Psi N: N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$ 
   $\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' } \bigcup (\text{set ' snd ' set (get-all-marked-decomposition } M'))$ 
  using  $\text{true-clss-clss-subset}[OF \ l \ N]$  by auto
have  $\text{is-marked (hd } Ls0)$  and  $LS: tl \ Ls0 = \text{seen1 } @ \ Ls1$ 
  using  $\text{get-all-marked-decomposition-hd-hd}[of \ M]$  unfolding  $Ls0 \ Ls1$  by auto

have  $LSM: \text{seen1 } @ \ Ls1 = M'$  using  $\text{get-all-marked-decomposition-decomp}[of \ M'] \ Ls1$  by auto
have  $M': \text{set } M' = \text{Union (set ' snd ' set (get-all-marked-decomposition } M'))$ 
   $\cup \{L \mid L. \text{is-marked } L \wedge L \in \text{set } M'\}$ 
  using  $\text{get-all-marked-decomposition-snd-union}$  by auto

{
  assume  $Ls0 \neq []$ 
  hence  $hd \ Ls0 \in \text{set } M$  using  $\text{get-all-marked-decomposition-fst-empty-or-hd-in-}M \ Ls0$  by blast
  hence  $N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\} \models_p (\lambda a. \{\#lit\text{-of } a\# \}) (hd \ Ls0)$ 
    using  $\langle \text{is-marked (hd } Ls0) \rangle$  by  $(metis \ (mono\text{-tags, lifting)} \ UnCI \ mem\text{-Collect-eq} \ \text{true-clss-clss-in})$ 
} note  $hd\text{-}Ls0 = \text{this}$ 

have l:  $(\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' } (\bigcup (\text{set ' snd ' set (get-all-marked-decomposition } M'))$ 
   $\cup \{L \mid L. \text{is-marked } L \wedge L \in \text{set } M'\})$ 
   $= (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' }$ 
   $\bigcup (\text{set ' snd ' set (get-all-marked-decomposition } M'))$ 
   $\cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M'\}$ 
  by auto
have  $N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M'\} \models_{ps}$ 
   $(\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' } (\bigcup (\text{set ' snd ' set (get-all-marked-decomposition } M'))$ 
   $\cup \{L \mid L. \text{is-marked } L \wedge L \in \text{set } M'\})$ 
  unfolding  $l$  using  $N$  by  $(\text{auto simp add: all-in-true-clss-clss})$ 
hence  $N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M'\} \models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set (tl } Ls0)$ 
  using  $M'$  unfolding  $LS \ LSM$  by auto
hence  $t: N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M'\}$ 
   $\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set (tl } Ls0)$ 
  by  $(blast \ \text{intro: all-in-true-clss-clss})$ 
hence  $N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$ 
   $\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set (tl } Ls0)$ 
  using  $M'\text{-in-}M \ \text{true-clss-clss-subset}[OF \ t,$ 
     $\text{of } N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M'\}]$ 
  by auto
hence  $N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\} \models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set } Ls0$ 
  using  $hd\text{-}Ls0$  by  $(\text{case-tac } Ls0, \text{auto})$ 

moreover have  $(\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set } Ls0 \cup N \models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set seen0}$ 
  using  $\text{Suc.premis unfolding } Ls0 \ \text{all-decomposition-implies-def}$  by simp
moreover have  $\bigwedge M \ Ma. (M::'a \ \text{literal multiset set}) \cup Ma \models_{ps} M$ 
  by  $(\text{simp add: all-in-true-clss-clss})$ 
ultimately have  $\Psi: N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\} \models_{ps}$ 
   $(\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set seen0}$ 
  by  $(meson \ \text{true-clss-clss-left-right true-clss-clss-union-and true-clss-clss-union-l-r})$ 
have  $(\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' (set seen0}$ 
   $\cup (\bigcup_{x \in \text{set (get-all-marked-decomposition } M')} . \text{set (snd } x)))$ 
   $= (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set seen0}$ 

```

$\cup (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' } (\bigcup_{x \in \text{set}} (\text{get-all-marked-decomposition } M'). \text{set } (\text{snd } x))$
by *auto*

hence *?case* **unfolding** *Ls0* **using** $\Psi \Psi N$ **by** *simp*

ultimately have *?case* **by** *auto*

ultimately show *?case* **by** *arith*

qed

lemma *all-decomposition-implies-propagated-lits-are-implied*:
assumes *all-decomposition-implies* N (*get-all-marked-decomposition* M)
shows $N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\} \models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set } M$
(is ?I \models_{ps} ?A)

proof –

have *?I* $\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' } \{L \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$
by (*auto intro: all-in-true-clss-clss*)

moreover have *?I* $\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' } \bigcup (\text{set 'snd 'set } (\text{get-all-marked-decomposition } M))$
using *all-decomposition-implies-trail-is-implied* *assms* **by** *blast*

ultimately have $N \cup \{\{\#lit\text{-of } m\# \} \mid m. \text{is-marked } m \wedge m \in \text{set } M\} \models_{ps} (\lambda m. \{\#lit\text{-of } m\# \}) \text{ ' } \bigcup (\text{set 'snd 'set } (\text{get-all-marked-decomposition } M))$
 $\cup (\lambda m. \{\#lit\text{-of } m\# \}) \text{ ' } \{m \mid m. \text{is-marked } m \wedge m \in \text{set } M\}$
by *blast*

thus *?thesis*

by (*metis* (*no-types*) *get-all-marked-decomposition-snd-union*[*of M*] *image-Un*)

qed

lemma *all-decomposition-implies-insert-single*:
all-decomposition-implies $N M \implies \text{all-decomposition-implies } (\text{insert } C N) M$
unfolding *all-decomposition-implies-def* **by** *auto*

13.4 Negation of Clauses

definition $CNot :: 'v \text{ clause} \Rightarrow 'v \text{ clauses where}$
 $CNot \psi = \{ \{\#-L\# \} \mid L. L \in \# \psi \}$

lemma *in-CNot-uminus*[*iff*]:
shows $\{\#L\# \} \in CNot \psi \longleftrightarrow -L \in \# \psi$
using *assms* **unfolding** *CNot-def* **by** *force*

lemma *CNot-singleton*[*simp*]: $CNot \{\#L\# \} = \{\{\#-L\# \}\}$ **unfolding** *CNot-def* **by** *auto*
lemma *CNot-empty*[*simp*]: $CNot \{\# \} = \{\}$ **unfolding** *CNot-def* **by** *auto*
lemma *CNot-plus*[*simp*]: $CNot (A + B) = CNot A \cup CNot B$ **unfolding** *CNot-def* **by** *auto*

lemma *CNot-eq-empty*[*iff*]:
 $CNot D = \{\} \longleftrightarrow D = \{\# \}$
unfolding *CNot-def* **by** (*auto simp add: multiset-eqI*)

lemma *in-CNot-implies-uminus*:
assumes $L \in \# D$
and $M \models_{as} CNot D$
shows $M \models_a \{\#-L\# \}$ **and** $-L \in \text{lits-of } M$
using *assms* **by** (*auto simp add: true-annot-def true-annot-def CNot-def*)

lemma *CNot-remdups-mset*[*simp*]:
 $CNot (\text{remdups-mset } A) = CNot A$

unfolding *CNot-def* **by** *auto*

lemma *Ball-CNot-Ball-mset[simp]* :
 $(\forall x \in CNot\ D. P\ x) \longleftrightarrow (\forall L \in \# D. P\ \{\# - L\# \})$
unfolding *CNot-def* **by** *auto*

lemma *consistent-CNot-not*:
assumes *consistent-interp I*
shows $I \models_s CNot\ \varphi \implies \neg I \models \varphi$
using *assms* **unfolding** *consistent-interp-def true-clss-def true-cls-def* **by** *auto*

lemma *total-not-true-cls-true-clss-CNot*:
assumes *total-over-m I {φ}* **and** $\neg I \models \varphi$
shows $I \models_s CNot\ \varphi$
using *assms* **unfolding** *total-over-m-def total-over-set-def true-clss-def true-cls-def CNot-def*
apply *clarify*
by (*case-tac L*) (*force intro: pos-lit-in-atms-of neg-lit-in-atms-of*)**+**

lemma *total-not-CNot*:
assumes *total-over-m I {φ}* **and** $\neg I \models_s CNot\ \varphi$
shows $I \models \varphi$
using *assms* *total-not-true-cls-true-clss-CNot* **by** *auto*

lemma *atms-of-ms-CNot-atms-of[simp]*:
 $atms-of-ms\ (CNot\ C) = atms-of\ C$
unfolding *atms-of-ms-def atms-of-def CNot-def* **by** *fastforce*

lemma *true-clss-clss-contradiction-true-clss-cls-false*:
 $C \in D \implies D \models_{ps} CNot\ C \implies D \models_p \{\#\}$
unfolding *true-clss-clss-def true-clss-cls-def total-over-m-def*
by (*metis Un-commute atms-of-empty atms-of-ms-CNot-atms-of atms-of-ms-insert atms-of-ms-union*
consistent-CNot-not insert-absorb sup-bot.left-neutral true-clss-def)

lemma *true-annots-CNot-all-atms-defined*:
assumes $M \models_{as} CNot\ T$ **and** $a1: L \in \# T$
shows $atm-of\ L \in atm-of\ \text{'lits-of } M$
by (*metis assms atm-of-uminus image-eqI in-CNot-implies-uminus(1) true-annot-singleton*)

lemma *true-clss-clss-false-left-right*:
assumes $\{\{\#L\#\}\} \cup B \models_p \{\#\}$
shows $B \models_{ps} CNot\ \{\#L\#\}$
unfolding *true-clss-clss-def true-clss-cls-def*

proof (*intro allI impI*)
fix *I*
assume
tot: total-over-m I (B ∪ CNot {#L#}) **and**
cons: consistent-interp I **and**
 $I \models_s B$
have *total-over-m I ({#L#} ∪ B)* **using** *tot* **by** *auto*
hence $\neg I \models_s insert\ \{\#L\#\}\ B$
using *assms cons* **unfolding** *true-clss-cls-def* **by** *simp*
thus $I \models_s CNot\ \{\#L\#\}$
using *tot I* **by** (*cases L*) *auto*

qed

lemma *true-annots-true-cls-def-iff-negation-in-model:*

$M \models_{as} CNot\ C \longleftrightarrow (\forall L \in \# C. -L \in lits\ of\ M)$

unfolding *CNot-def true-annots-true-cls true-clss-def* **by** *auto*

lemma *consistent-CNot-not-tautology:*

consistent-interp $M \implies M \models_s CNot\ D \implies \neg tautology\ D$

by (*metis atms-of-ms-CNot-atms-of consistent-CNot-not satisfiable-carac' satisfiable-def tautology-def total-over-m-def*)

lemma *atms-of-ms-CNot-atms-of-ms: atms-of-ms (CNot CC) = atms-of-ms {CC}*

by *simp*

lemma *total-over-m-CNot-toal-over-m[simp]:*

total-over-m $I\ (CNot\ C) = total-over-set\ I\ (atms-of\ C)$

unfolding *total-over-m-def total-over-set-def* **by** *auto*

lemma *uminus-lit-swap: $\neg(a::'a\ literal) = i \longleftrightarrow a = -i$*

by *auto*

lemma *true-clss-cls-plus-CNot:*

assumes *CC-L: $A \models_p CC + \{\#L\# \}$*

and *CNot-CC: $A \models_{ps} CNot\ CC$*

shows $A \models_p \{\#L\# \}$

unfolding *true-clss-clss-def true-clss-cls-def CNot-def total-over-m-def*

proof (*intro allI impI*)

fix I

assume *tot: total-over-set I (atms-of-ms (A \cup { $\{\#L\# \}$ }))*

and *cons: consistent-interp I*

and $I: I \models_s A$

let $?I = I \cup \{Pos\ P | P. P \in atms-of\ CC \wedge P \notin atm-of\ 'I\}$

have *cons': consistent-interp ?I*

using *cons unfolding consistent-interp-def*

by (*auto simp add: uminus-lit-swap atms-of-def rev-image-eqI*)

have $I': ?I \models_s A$

using *I true-clss-union-increase* **by** *blast*

have *tot-CNot: total-over-m ?I (A \cup CNot CC)*

using *tot atms-of-s-def* **by** (*fastforce simp add: total-over-m-def total-over-set-def*)

hence *tot-I-A-CC-L: total-over-m ?I (A \cup {CC + { $\{\#L\# \}$ }})*

using *tot unfolding total-over-m-def total-over-set-atm-of* **by** *auto*

hence $?I \models CC + \{\#L\# \}$ **using** *CC-L cons' I'* **unfolding** *true-clss-cls-def* **by** *blast*

moreover

have $?I \models_s CNot\ CC$ **using** *CNot-CC cons' I'* **tot-CNot** **unfolding** *true-clss-clss-def* **by** *auto*

hence $\neg A \models_p CC$

by (*metis (no-types, lifting) I' atms-of-ms-CNot-atms-of-ms atms-of-ms-union cons' consistent-CNot-not tot-CNot total-over-m-def true-clss-cls-def*)

hence $\neg ?I \models CC$ **using** $\langle ?I \models_s CNot\ CC \rangle$ *cons'* *consistent-CNot-not* **by** *blast*

ultimately have $?I \models \{\#L\# \}$ **by** *blast*

thus $I \models \{\#L\# \}$

by (*metis (no-types, lifting) atms-of-ms-union cons' consistent-CNot-not tot total-not-CNot total-over-m-def total-over-set-union true-clss-union-increase*)

qed

lemma *true-annots-CNot-lit-of-notin-skip:*

assumes *LM: $L \# M \models_{as} CNot\ A$* **and** *LA: $lit-of\ L \notin \# A - lit-of\ L \notin \# A$*

shows $M \models_{as} CNot\ A$
using *LM unfolding true-annots-def Ball-def*
proof (*intro allI impI*)
fix l
assume $H: \forall x. x \in CNot\ A \longrightarrow L \# M \models_a x$ **and** $l: l \in CNot\ A$
hence $L \# M \models_a l$ **by** *auto*
thus $M \models_a l$ **using** *LA l by (cases L) (auto simp add: CNot-def)*
qed

lemma *true-clss-clss-union-false-true-clss-clss-cnot*:
 $A \cup \{B\} \models_{ps} \{\{\#\}\} \longleftrightarrow A \models_{ps} CNot\ B$
using *total-not-CNot consistent-CNot-not unfolding total-over-m-def true-clss-clss-def*
by *fastforce*

lemma *true-annot-remove-hd-if-notin-vars*:
assumes $a \# M' \models_a D$
and *atm-of (lit-of a) \notin atms-of D*
shows $M' \models_a D$
using *assms true-clss-remove-hd-if-notin-vars unfolding true-annot-def* **by** *auto*

lemma *true-annot-remove-if-notin-vars*:
assumes $M @ M' \models_a D$
and $\forall x \in \text{atms-of } D. x \notin \text{atm-of ' lits-of } M$
shows $M' \models_a D$
using *assms apply (induct M, simp)*
using *true-annot-remove-hd-if-notin-vars* **by** *force+*

lemma *true-annots-remove-if-notin-vars*:
assumes $M @ M' \models_{as} D$
and $\forall x \in \text{atms-of-ms } D. x \notin \text{atm-of ' lits-of } M$
shows $M' \models_{as} D$ **unfolding** *true-annots-def*
using *assms true-annot-remove-if-notin-vars[of M M']*
unfolding *true-annots-def atms-of-ms-def* **by** *force*

lemma *all-variables-defined-not-imply-cnot*:
assumes $\forall s \in \text{atms-of-ms } \{B\}. s \in \text{atm-of ' lits-of } A$
and $\neg A \models_a B$
shows $A \models_{as} CNot\ B$
unfolding *true-annot-def true-annots-def Ball-def CNot-def true-lit-def*
proof (*clarify, rule ccontr*)
fix L
assume $LB: L \in \# B$ **and** $\neg \text{lits-of } A \models_l - L$
hence $\text{atm-of } L \in \text{atm-of ' lits-of } A$
using *assms(1) by (simp add: atm-of-lit-in-atms-of lits-of-def)*
hence $L \in \text{lits-of } A \vee -L \in \text{lits-of } A$
using *atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set* **by** *metis*
hence $L \in \text{lits-of } A$ **using** $\langle \neg \text{lits-of } A \models_l - L \rangle$ **by** *auto*
thus *False*
using LB *assms(2) unfolding true-annot-def true-lit-def true-clss-def Bex-mset-def*
by *blast*
qed

lemma *CNot-union-mset[simp]*:
 $CNot\ (A \# \cup B) = CNot\ A \cup CNot\ B$
unfolding *CNot-def* **by** *auto*

13.5 Other

abbreviation $\text{no-dup } L \equiv \text{distinct } (\text{map } (\lambda l. \text{atm-of } (\text{lit-of } l)) L)$

lemma no-dup-rev[simp] :
 $\text{no-dup } (\text{rev } M) \longleftrightarrow \text{no-dup } M$
by $(\text{auto simp: rev-map[symmetric]})$

lemma $\text{no-dup-length-eq-card-atm-of-lits-of}$:
assumes $\text{no-dup } M$
shows $\text{length } M = \text{card } (\text{atm-of } ' \text{lits-of } M)$
using $\text{assms unfolding lits-of-def by (induct M) (auto simp add: image-image)}$

lemma $\text{distinctconsistent-interp}$:
 $\text{no-dup } M \implies \text{consistent-interp } (\text{lits-of } M)$
proof $(\text{induct } M)$
case Nil
show $?case$ **by** auto
next
case $(\text{Cons } L M)$
hence $a1: \text{consistent-interp } (\text{lits-of } M)$ **by** auto
have $a2: \text{atm-of } (\text{lit-of } L) \notin (\lambda l. \text{atm-of } (\text{lit-of } l)) ' \text{set } M$ **using** $\text{Cons.premis by auto}$
have $\text{undefined-lit } M (\text{lit-of } L)$
using $a2 \text{ image-iff unfolding defined-lit-def by fastforce}$
thus $?case$
using $a1$ **by** simp
qed

lemma $\text{distinct-get-all-marked-decomposition-no-dup}$:
assumes $(a, b) \in \text{set } (\text{get-all-marked-decomposition } M)$
and $\text{no-dup } M$
shows $\text{no-dup } (a @ b)$
using assms by force

lemma $\text{true-annots-lit-of-notin-skip}$:
assumes $L \# M \models_{\text{as}} \text{CNot } A$
and $\neg \text{lit-of } L \notin \# A$
and $\text{no-dup } (L \# M)$
shows $M \models_{\text{as}} \text{CNot } A$
proof $-$
have $\forall l \in \# A. \neg l \in \text{lits-of } (L \# M)$
using $\text{assms(1) in-CNot-implies-uminus(2) by blast}$
moreover
have $\text{atm-of } (\text{lit-of } L) \notin \text{atm-of } ' \text{lits-of } M$
using $\text{assms(3) unfolding lits-of-def by force}$
hence $\neg \text{lit-of } L \notin \text{lits-of } M$ **unfolding** lits-of-def
by $(\text{metis (no-types) atm-of-uminus imageI})$
ultimately have $\forall l \in \# A. \neg l \in \text{lits-of } M$
using $\text{assms(2) unfolding Ball-mset-def by (metis insertE lits-of-cons uminus-of-uminus-id)}$
thus $?thesis$ **by** $(\text{auto simp add: true-annots-def})$
qed

type-synonym $'v \text{ clauses} = 'v \text{ clause multiset}$

abbreviation $\text{true-annots-mset (infix } \models_{\text{asm}} 50) \text{ where}$
 $I \models_{\text{asm}} C \equiv I \models_{\text{as}} (\text{set-mset } C)$

abbreviation *true-clss-clss-m*:: 'a clauses \Rightarrow 'a clauses \Rightarrow bool (**infix** \models_{psm} 50) **where**
 $I \models_{psm} C \equiv \text{set-mset } I \models_{ps} (\text{set-mset } C)$

Analog of $\llbracket ?N \models_{ps} ?B; ?A \subseteq ?B \rrbracket \Longrightarrow ?N \models_{ps} ?A$

lemma *true-clss-clssm-subsetE*: $N \models_{psm} B \Longrightarrow A \subseteq\# B \Longrightarrow N \models_{psm} A$
using *set-mset-mono true-clss-clss-subsetE* **by** *blast*

abbreviation *true-clss-clss-m*:: 'a clauses \Rightarrow 'a clause \Rightarrow bool (**infix** \models_{pm} 50) **where**
 $I \models_{pm} C \equiv \text{set-mset } I \models_p C$

abbreviation *distinct-mset-mset* :: 'a multiset multiset \Rightarrow bool **where**
 $\text{distinct-mset-mset } \Sigma \equiv \text{distinct-mset-set } (\text{set-mset } \Sigma)$

abbreviation *all-decomposition-implies-m* **where**
 $\text{all-decomposition-implies-m } A B \equiv \text{all-decomposition-implies } (\text{set-mset } A) B$

abbreviation *atms-of-msu* **where**
 $\text{atms-of-msu } U \equiv \text{atms-of-ms } (\text{set-mset } U)$

abbreviation *true-clss-m*:: 'a interp \Rightarrow 'a clauses \Rightarrow bool (**infix** \models_{sm} 50) **where**
 $I \models_{sm} C \equiv I \models_s \text{set-mset } C$

abbreviation *true-clss-ext-m* (**infix** \models_{sextm} 49) **where**
 $I \models_{sextm} C \equiv I \models_{sext} \text{set-mset } C$

end

theory *CDCL-NOT*

imports *Partial-Annotated-Clausal-Logic List-More Wellfounded-More Partial-Clausal-Logic*
begin

14 NOT's CDCL

sledgehammer-params[*verbose, prover=e spass z3 cvc4 verit remote-vampire*]

declare *set-mset-minus-replicate-mset*[*simp*]

14.1 Auxiliary Lemmas and Measure

lemma *no-dup-cannot-not-lit-and-uminus*:
 $\text{no-dup } M \Longrightarrow \neg \text{lit-of } xa = \text{lit-of } x \Longrightarrow x \in \text{set } M \Longrightarrow xa \notin \text{set } M$
by (*metis atm-of-uminus distinct-map inj-on-eq-iff uminus-not-id*)

lemma *true-clss-single-iff-incl*:
 $I \models_s \text{single } B \longleftrightarrow B \subseteq I$
unfolding *true-clss-def* **by** *auto*

lemma *atms-of-ms-single-atm-of*[*simp*]:
 $\text{atms-of-ms } \{\{\# \text{lit-of } L\# \} \mid L. P L\} = \text{atm-of } \{ \text{lit-of } L \mid L. P L \}$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-uminus-lit-atm-of-lit-of*:
 $\text{atms-of } \{\# \neg \text{lit-of } x. x \in\# A\# \} = \text{atm-of } \{ (\text{lit-of } (\text{set-mset } A)) \}$
unfolding *atms-of-def* **by** (*auto simp add: Fun.image-comp*)

lemma *atms-of-ms-single-image-atm-of-lit-of*:

atms-of-ms $((\lambda x. \{\#lit\text{-of } x\}) \text{ ' } A) = atm\text{-of ' } (lit\text{-of ' } A)$
unfolding *atms-of-ms-def* **by** *auto*

This measure can also be seen as the increasing lexicographic order: it is an order on bounded sequences, when each element is bounded. The proof involves a measure like the one defined here (the same?).

definition $\mu_C :: nat \Rightarrow nat \Rightarrow nat \text{ list} \Rightarrow nat$ **where**
 $\mu_C \text{ s b M} \equiv (\sum i=0..<length \text{ M}. M!i * b^\wedge (s + i - length \text{ M}))$

lemma $\mu_C\text{-nil}[simp]$:
 $\mu_C \text{ s b []} = 0$
unfolding $\mu_C\text{-def}$ **by** *auto*

lemma $\mu_C\text{-single}[simp]$:
 $\mu_C \text{ s b [L]} = L * b^\wedge (s - Suc \ 0)$
unfolding $\mu_C\text{-def}$ **by** *auto*

lemma *set-sum-atLeastLessThan-add*:
 $(\sum i=k..<k+(b::nat). f \ i) = (\sum i=0..<b. f \ (k + i))$
by (*induction b*) *auto*

lemma *set-sum-atLeastLessThan-Suc*:
 $(\sum i=1..<Suc \ j. f \ i) = (\sum i=0..<j. f \ (Suc \ i))$
using *set-sum-atLeastLessThan-add*[*of - 1 j*] **by** *force*

lemma $\mu_C\text{-cons}$:
 $\mu_C \text{ s b (L \# M)} = L * b^\wedge (s - 1 - length \text{ M}) + \mu_C \text{ s b M}$
proof –
have $\mu_C \text{ s b (L \# M)} = (\sum i=0..<length \text{ (L\#M)}. (L\#M)!i * b^\wedge (s + i - length \text{ (L\#M)}))$
unfolding $\mu_C\text{-def}$ **by** *blast*
also have $\dots = (\sum i=0..<1. (L\#M)!i * b^\wedge (s + i - length \text{ (L\#M)}))$
 $+ (\sum i=1..<length \text{ (L\#M)}. (L\#M)!i * b^\wedge (s + i - length \text{ (L\#M)}))$
by (*rule setsum-add-nat-ivl[symmetric]*) *simp-all*
finally have $\mu_C \text{ s b (L \# M)} = L * b^\wedge (s - 1 - length \text{ M})$
 $+ (\sum i=1..<length \text{ (L\#M)}. (L\#M)!i * b^\wedge (s + i - length \text{ (L\#M)}))$
by *auto*
moreover {
have $(\sum i=1..<length \text{ (L\#M)}. (L\#M)!i * b^\wedge (s + i - length \text{ (L\#M)})) =$
 $(\sum i=0..<length \text{ (M)}. (L\#M)!(Suc \ i) * b^\wedge (s + (Suc \ i) - length \text{ (L\#M)}))$
unfolding *length-Cons set-sum-atLeastLessThan-Suc* **by** *blast*
also have $\dots = (\sum i=0..<length \text{ (M)}. M!i * b^\wedge (s + i - length \text{ M}))$
by *auto*
finally have $(\sum i=1..<length \text{ (L\#M)}. (L\#M)!i * b^\wedge (s + i - length \text{ (L\#M)})) = \mu_C \text{ s b M}$
unfolding $\mu_C\text{-def}$.
}
ultimately show *?thesis* **by** *presburger*
qed

lemma $\mu_C\text{-append}$:
assumes $s \geq length \text{ (M@M')}$
shows $\mu_C \text{ s b (M@M')} = \mu_C (s - length \text{ M'}) \text{ b M} + \mu_C \text{ s b M'}$
proof –
have $\mu_C \text{ s b (M@M')} = (\sum i=0..<length \text{ (M@M')}. (M@M')!i * b^\wedge (s + i - length \text{ (M@M')}))$
unfolding $\mu_C\text{-def}$ **by** *blast*
moreover then have $\dots = (\sum i=0..<length \text{ M}. (M@M')!i * b^\wedge (s + i - length \text{ (M@M')}))$

$+$ $(\sum i=length\ M..<length\ (M@M')). (M@M')!i * b^\wedge (s+i - length\ (M@M')))$
by *(auto intro!: setsum-add-nat-ivl[symmetric])*
moreover
have $\forall i \in \{0..<length\ M\}. (M@M')!i * b^\wedge (s+i - length\ (M@M')) = M!i * b^\wedge (s - length\ M' + i - length\ M)$
using $\langle s \geq length\ (M@M') \rangle$ **by** *(auto simp add: nth-append ac-simps)*
then have $\mu_C\ (s - length\ M')\ b\ M = (\sum i=0..<length\ M. (M@M')!i * b^\wedge (s+i - length\ (M@M')))$
unfolding μ_C -def **by** *auto*
ultimately have $\mu_C\ s\ b\ (M@M') = \mu_C\ (s - length\ M')\ b\ M$
 $+$ $(\sum i=length\ M..<length\ (M@M')). (M@M')!i * b^\wedge (s+i - length\ (M@M')))$
by *auto*
moreover {
have $(\sum i=length\ M..<length\ (M@M')). (M@M')!i * b^\wedge (s+i - length\ (M@M')) =$
 $(\sum i=0..<length\ M'. M!i * b^\wedge (s+i - length\ M'))$
unfolding *length-append set-sum-atLeastLessThan-add* **by** *auto*
then have $(\sum i=length\ M..<length\ (M@M')). (M@M')!i * b^\wedge (s+i - length\ (M@M')) = \mu_C\ s\ b\ M'$
unfolding μ_C -def .
}
ultimately show *?thesis* **by** *presburger*
qed

lemma μ_C -cons-non-empty-inf:
assumes *M-ge-1*: $\forall i \in set\ M. i \geq 1$ **and** $M: M \neq []$
shows $\mu_C\ s\ b\ M \geq b^\wedge (s - length\ M)$
using *assms* **by** *(cases M) (auto simp: mult-eq-if μ_C -cons)*

Duplicate of " /src/HOL/ex/NatSum.thy" (but generalized to $(0::'a) \leq k$)

lemma *sum-of-powers*: $0 \leq k \implies (k - 1) * (\sum i=0..<n. k^\wedge i) = k^\wedge n - (1::nat)$
apply *(cases k = 0)*
apply *(cases n; simp)*
by *(induct n) (auto simp: Nat.nat-distrib)*

In the degenerated cases, we only have the large inequality holds. In the other cases, the following strict inequality holds:

lemma μ_C -bounded-non-degenerated:
fixes $b :: nat$
assumes
 $b > 0$ **and**
 $M \neq []$ **and**
 $M-le$: $\forall i < length\ M. M!i < b$ **and**
 $s \geq length\ M$
shows $\mu_C\ s\ b\ M < b^\wedge s$

proof -
consider $(b1)\ b = 1 \mid (b)\ b > 1$ **using** $\langle b > 0 \rangle$ **by** *(cases b) auto*
then show *?thesis*
proof *cases*
case *b1*
then have $\forall i < length\ M. M!i = 0$ **using** *M-le* **by** *auto*
then have $\mu_C\ s\ b\ M = 0$ **unfolding** μ_C -def **by** *auto*
then show *?thesis* **using** $\langle b > 0 \rangle$ **by** *auto*
next
case *b*
have $\forall i \in \{0..<length\ M\}. M!i * b^\wedge (s+i - length\ M) \leq (b-1) * b^\wedge (s+i - length\ M)$

```

    using M-le ⟨b > 1⟩ by auto
  then have  $\mu_C s b M \leq (\sum i=0..<\text{length } M. (b-1) * b^\wedge (s+i - \text{length } M))$ 
    using ⟨M≠[]⟩ ⟨b>0⟩ unfolding  $\mu_C\text{-def}$  by (auto intro: setsum-mono)
  also
    have  $\forall i \in \{0..<\text{length } M\}. (b-1) * b^\wedge (s+i - \text{length } M) = (b-1) * b^\wedge i * b^\wedge (s - \text{length } M)$ 
      by (metis Nat.add-diff-assoc2 add.commute assms(4) mult.assoc power-add)
    then have  $(\sum i=0..<\text{length } M. (b-1) * b^\wedge (s+i - \text{length } M))$ 
      =  $(\sum i=0..<\text{length } M. (b-1) * b^\wedge i * b^\wedge (s - \text{length } M))$ 
      by (auto simp add: ac-simps)
    also have  $\dots = (\sum i=0..<\text{length } M. b^\wedge i) * b^\wedge (s - \text{length } M) * (b-1)$ 
      by (simp add: setsum-left-distrib setsum-right-distrib ac-simps)
    finally have  $\mu_C s b M \leq (\sum i=0..<\text{length } M. b^\wedge i) * (b-1) * b^\wedge (s - \text{length } M)$ 
      by (simp add: ac-simps)

  also
    have  $(\sum i=0..<\text{length } M. b^\wedge i) * (b-1) = b^\wedge (\text{length } M) - 1$ 
      using sum-of-powers[of b length M] ⟨b>1⟩
      by (auto simp add: ac-simps)
    finally have  $\mu_C s b M \leq (b^\wedge (\text{length } M) - 1) * b^\wedge (s - \text{length } M)$ 
      by auto
    also have  $\dots < b^\wedge (\text{length } M) * b^\wedge (s - \text{length } M)$ 
      using ⟨b>1⟩ by auto
    also have  $\dots = b^\wedge s$ 
      by (metis assms(4) le-add-diff-inverse power-add)
    finally show ?thesis unfolding  $\mu_C\text{-def}$  by (auto simp add: ac-simps)
qed
qed

```

In the degenerate case $b = (0::'a)$, the list M is empty (since the list cannot contain any element).

```

lemma  $\mu_C\text{-bounded}$ :
  fixes b :: nat
  assumes
    M-le:  $\forall i < \text{length } M. M!i < b$  and
    s  $\geq \text{length } M$ 
    b > 0
  shows  $\mu_C s b M < b^\wedge s$ 
proof -
  consider (M0)  $M = [] \mid (M) b > 0$  and  $M \neq []$ 
  using M-le by (cases b, cases M) auto
  then show ?thesis
  proof cases
    case M0
      then show ?thesis using M-le ⟨b > 0⟩ by auto
    next
      case M
        show ?thesis using  $\mu_C\text{-bounded-non-degenerated}[OF M \text{ assms}(1,2)]$  by arith
  qed
qed

```

When $b = 0$, we cannot show that the measure is empty, since $0^0 = 1$.

```

lemma  $\mu_C\text{-base-0}$ :
  assumes  $\text{length } M \leq s$ 
  shows  $\mu_C s 0 M \leq M!0$ 
proof -

```

```

{
  assume  $s = \text{length } M$ 
  moreover {
    fix  $n$ 
    have  $(\sum_{i=0..<n}. M ! i * (0::\text{nat}) ^ i) \leq M ! 0$ 
    apply (induction  $n$  rule: nat-induct)
    by simp (case-tac  $n$ , auto)
  }
  ultimately have ?thesis unfolding  $\mu_C$ -def by auto
}
moreover
{
  assume  $\text{length } M < s$ 
  then have  $\mu_C s 0 M = 0$  unfolding  $\mu_C$ -def by auto}
ultimately show ?thesis using assms unfolding  $\mu_C$ -def by linarith
qed

```

14.2 Initial definitions

14.2.1 The state

We define here an abstraction over operation on the state we are manipulating.

```

locale dpll-state =
  fixes
    trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
    clauses :: 'st  $\Rightarrow$  'v clauses and
    prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
    tl-trail :: 'st  $\Rightarrow$  'st and
    add-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
    remove-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st
  assumes
    trail-prepend-trail[simp]:
       $\bigwedge st L. \text{undefined-lit } (\text{trail } st) (\text{lit-of } L) \Longrightarrow \text{trail } (\text{prepend-trail } L \text{ } st) = L \# \text{trail } st$ 
      and
    tl-trail[simp]: trail (tl-trail  $S$ ) = tl (trail  $S$ ) and
    trail-add-clNOT[simp]:  $\bigwedge st C. \text{no-dup } (\text{trail } st) \Longrightarrow \text{trail } (\text{add-cl}_{NOT} C \text{ } st) = \text{trail } st$  and
    trail-remove-clNOT[simp]:  $\bigwedge st C. \text{trail } (\text{remove-cl}_{NOT} C \text{ } st) = \text{trail } st$  and

    clauses-prepend-trail[simp]:
       $\bigwedge st L. \text{undefined-lit } (\text{trail } st) (\text{lit-of } L) \Longrightarrow \text{clauses } (\text{prepend-trail } L \text{ } st) = \text{clauses } st$ 
      and
    clauses-tl-trail[simp]:  $\bigwedge st. \text{clauses } (\text{tl-trail } st) = \text{clauses } st$  and
    clauses-add-clNOT[simp]:
       $\bigwedge st C. \text{no-dup } (\text{trail } st) \Longrightarrow \text{clauses } (\text{add-cl}_{NOT} C \text{ } st) = \{\#C\} + \text{clauses } st$  and
    clauses-remove-clNOT[simp]:  $\bigwedge st C. \text{clauses } (\text{remove-cl}_{NOT} C \text{ } st) = \text{remove-mset } C (\text{clauses } st)$ 
  begin

  function reduce-trail-toNOT :: ('v, unit, unit) marked-lits  $\Rightarrow$  'st  $\Rightarrow$  'st where
    reduce-trail-toNOT  $F S$  =
      (if length (trail  $S$ ) = length  $F \vee \text{trail } S = []$  then  $S$  else reduce-trail-toNOT  $F$  (tl-trail  $S$ ))
  by fast+
  termination by (relation measure ( $\lambda(-, S). \text{length } (\text{trail } S)$ )) auto
  declare reduce-trail-toNOT.simps[simp del]

  lemma

```

shows

reduce-trail-to_{NOT}-nil[simp]: $\text{trail } S = [] \implies \text{reduce-trail-to}_{\text{NOT}} F S = S$ **and**
reduce-trail-to_{NOT}-eq-length[simp]: $\text{length } (\text{trail } S) = \text{length } F \implies \text{reduce-trail-to}_{\text{NOT}} F S = S$
by (auto simp: *reduce-trail-to_{NOT}.simps*)

lemma *reduce-trail-to_{NOT}-length-ne*[simp]:

$\text{length } (\text{trail } S) \neq \text{length } F \implies \text{trail } S \neq [] \implies$
 $\text{reduce-trail-to}_{\text{NOT}} F S = \text{reduce-trail-to}_{\text{NOT}} F (\text{tl-trail } S)$
by (auto simp: *reduce-trail-to_{NOT}.simps*)

lemma *trail-reduce-trail-to_{NOT}-length-le*:

assumes $\text{length } F > \text{length } (\text{trail } S)$
shows $\text{trail } (\text{reduce-trail-to}_{\text{NOT}} F S) = []$
using *assms* **by** (induction $F S$ rule: *reduce-trail-to_{NOT}.induct*)
(simp add: less-imp-diff-less reduce-trail-to_{NOT}.simps)

lemma *trail-reduce-trail-to_{NOT}-nil*[simp]:

$\text{trail } (\text{reduce-trail-to}_{\text{NOT}} [] S) = []$
by (induction $[]:: ('v, \text{unit}, \text{unit}) \text{ marked-lits } S$ rule: *reduce-trail-to_{NOT}.induct*)
(simp add: less-imp-diff-less reduce-trail-to_{NOT}.simps)

lemma *clauses-reduce-trail-to_{NOT}-nil*:

$\text{clauses } (\text{reduce-trail-to}_{\text{NOT}} [] S) = \text{clauses } S$
by (induction $[]:: ('v, \text{unit}, \text{unit}) \text{ marked-lits } S$ rule: *reduce-trail-to_{NOT}.induct*)
(simp add: less-imp-diff-less reduce-trail-to_{NOT}.simps)

lemma *reduce-trail-to_{NOT}-skip-beginning*:

assumes $\text{trail } S = F' @ F$
shows $\text{trail } (\text{reduce-trail-to}_{\text{NOT}} F S) = F$
using *assms* **by** (induction F' arbitrary: S) auto

lemma *reduce-trail-to_{NOT}-clauses*[simp]:

$\text{clauses } (\text{reduce-trail-to}_{\text{NOT}} F S) = \text{clauses } S$
by (induction $F S$ rule: *reduce-trail-to_{NOT}.induct*)
(simp add: less-imp-diff-less reduce-trail-to_{NOT}.simps)

abbreviation *trail-weight* **where**

$\text{trail-weight } S \equiv \text{map } ((\lambda l. 1 + \text{length } l) \circ \text{snd}) (\text{get-all-marked-decomposition } (\text{trail } S))$

definition *state-eq_{NOT}* :: $'st \Rightarrow 'st \Rightarrow \text{bool}$ (*infix* ~ 50) **where**

$S \sim T \longleftrightarrow \text{trail } S = \text{trail } T \wedge \text{clauses } S = \text{clauses } T$

lemma *state-eq_{NOT}-ref*[simp]:

$S \sim S$
unfolding *state-eq_{NOT}-def* **by** auto

lemma *state-eq_{NOT}-sym*:

$S \sim T \longleftrightarrow T \sim S$
unfolding *state-eq_{NOT}-def* **by** auto

lemma *state-eq_{NOT}-trans*:

$S \sim T \implies T \sim U \implies S \sim U$
unfolding *state-eq_{NOT}-def* **by** auto

lemma

shows

state-eq_{NOT}-trail: $S \sim T \implies \text{trail } S = \text{trail } T$ **and**
state-eq_{NOT}-clauses: $S \sim T \implies \text{clauses } S = \text{clauses } T$

unfolding *state-eq_{NOT}-def* **by** *auto*

lemmas *state-simp_{NOT}[simp]* = *state-eq_{NOT}-trail state-eq_{NOT}-clauses*

lemma *trail-eq-reduce-trail-to_{NOT}-eq*:

trail $S = \text{trail } T \implies \text{trail } (\text{reduce-trail-to}_{\text{NOT}} F S) = \text{trail } (\text{reduce-trail-to}_{\text{NOT}} F T)$

apply (*induction* $F S$ *arbitrary*: T *rule*: *reduce-trail-to_{NOT}.induct*)

by (*metis* *tl-trail reduce-trail-to_{NOT}-eq-length reduce-trail-to_{NOT}-length-ne reduce-trail-to_{NOT}-nil*)

lemma *reduce-trail-to_{NOT}-state-eq_{NOT}-compatible*:

assumes ST : $S \sim T$

shows *reduce-trail-to_{NOT}* $F S \sim \text{reduce-trail-to}_{\text{NOT}} F T$

proof –

have *clauses*(*reduce-trail-to_{NOT}* $F S$) = *clauses* (*reduce-trail-to_{NOT}* $F T$)

using ST **by** *auto*

moreover have *trail* (*reduce-trail-to_{NOT}* $F S$) = *trail* (*reduce-trail-to_{NOT}* $F T$)

using *trail-eq-reduce-trail-to_{NOT}-eq*[*of* $S T F$] ST **by** *auto*

ultimately show *?thesis* **by** (*auto simp del: state-simp_{NOT} simp: state-eq_{NOT}-def*)

qed

lemma *trail-reduce-trail-to_{NOT}-add-cl_{NOT}[simp]*:

no-dup (*trail* S) \implies

trail (*reduce-trail-to_{NOT}* F (*add-cl_{NOT}* $C S$)) = *trail* (*reduce-trail-to_{NOT}* $F S$)

by (*rule* *trail-eq-reduce-trail-to_{NOT}-eq*) *simp*

lemma *reduce-trail-to_{NOT}-trail-tl-trail-decomp[simp]*:

trail $S = F' @ \text{Marked } K () \# F \implies$

(*trail* (*reduce-trail-to_{NOT}* F (*tl-trail* S))) = F

apply (*rule* *reduce-trail-to_{NOT}-skip-beginning*[*of* - *tl* ($F' @ \text{Marked } K () \# []$)])

by (*cases* F') (*auto simp add:tl-append reduce-trail-to_{NOT}-skip-beginning*)

end

14.2.2 Definition of the operation

locale *propagate-ops* =

dpll-state trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT} **for**

trail :: $'st \Rightarrow ('v, \text{unit}, \text{unit}) \text{ marked-lits}$ **and**

clauses :: $'st \Rightarrow 'v \text{ clauses}$ **and**

prepend-trail :: $('v, \text{unit}, \text{unit}) \text{ marked-lit} \Rightarrow 'st \Rightarrow 'st$ **and**

tl-trail :: $'st \Rightarrow 'st$ **and**

add-cl_{NOT} remove-cl_{NOT} :: $'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$ **and**

propagate-cond :: $('v, \text{unit}, \text{unit}) \text{ marked-lit} \Rightarrow 'st \Rightarrow \text{bool}$

begin

inductive *propagate_{NOT}* :: $'st \Rightarrow 'st \Rightarrow \text{bool}$ **where**

propagate_{NOT}[*intro*]: $C + \{\#L\# \} \in \# \text{ clauses } S \implies \text{trail } S \models_{\text{as}} C \text{Not } C$

$\implies \text{undefined-lit } (\text{trail } S) L$

$\implies \text{propagate-cond } (\text{Propagated } L ()) S$

$\implies T \sim \text{prepend-trail } (\text{Propagated } L ()) S$

$\implies \text{propagate}_{\text{NOT}} S T$

inductive-cases *propagateE*[*elim*]: *propagate_{NOT}* $S T$

end

```

locale decide-ops =
  dpll-state trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT for
    trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
    clauses :: 'st  $\Rightarrow$  'v clauses and
    prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
    tl-trail :: 'st  $\Rightarrow$  'st and
    add-clsNOT remove-clsNOT:: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st
begin
inductive decideNOT :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
decideNOT[intro]: undefined-lit (trail S) L  $\Longrightarrow$  atm-of L  $\in$  atms-of-msu (clauses S)
   $\Longrightarrow$  T  $\sim$  prepend-trail (Marked L ()) S
   $\Longrightarrow$  decideNOT S T

inductive-cases decideE[elim]: decideNOT S S'
end

locale backjumping-ops =
  dpll-state trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT
for
  trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
  clauses :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clsNOT remove-clsNOT:: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st +
fixes
  backjump-conds :: 'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool
begin
inductive backjump where
trail S = F' @ Marked K () # F
   $\Longrightarrow$  T  $\sim$  prepend-trail (Propagated L ()) (reduce-trail-toNOT F S)
   $\Longrightarrow$  C  $\in$  # clauses S
   $\Longrightarrow$  trail S  $\models_{as}$  CNot C
   $\Longrightarrow$  undefined-lit F L
   $\Longrightarrow$  atm-of L  $\in$  atms-of-msu (clauses S)  $\cup$  atm-of ' (lits-of (trail S))
   $\Longrightarrow$  clauses S  $\models_{pm}$  C' + {#L#}
   $\Longrightarrow$  F  $\models_{as}$  CNot C'
   $\Longrightarrow$  backjump-conds C' L S T
   $\Longrightarrow$  backjump S T
inductive-cases backjumpE: backjump S T
end

```

14.3 DPLL with backjumping

```

locale dpll-with-backjumping-ops =
  dpll-state trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT +
  propagate-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT propagate-conds +
  decide-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT +
  backjumping-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT backjump-conds
for
  trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
  clauses :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clsNOT remove-clsNOT:: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  propagate-conds :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  bool and

```

$inv :: 'st \Rightarrow bool$ **and**
 $backjump\text{-}conds :: 'v\ clause \Rightarrow 'v\ literal \Rightarrow 'st \Rightarrow 'st \Rightarrow bool +$
assumes
 $bj\text{-}can\text{-}jump:$
 $\bigwedge S\ C\ F'\ K\ F\ L.$
 $inv\ S \Longrightarrow$
 $no\text{-}dup\ (trail\ S) \Longrightarrow$
 $trail\ S = F' @ Marked\ K\ () \# F \Longrightarrow$
 $C \in \# clauses\ S \Longrightarrow$
 $trail\ S \models_{as} CNot\ C \Longrightarrow$
 $undefined\text{-}lit\ F\ L \Longrightarrow$
 $atm\text{-}of\ L \in atms\text{-}of\text{-}msu\ (clauses\ S) \cup atm\text{-}of\ ' (lits\text{-}of\ (F' @ Marked\ K\ () \# F)) \Longrightarrow$
 $clauses\ S \models_{pm} C' + \{\#L\# \} \Longrightarrow$
 $F \models_{as} CNot\ C' \Longrightarrow$
 $\neg no\text{-}step\ backjump\ S$
begin

We cannot add a like condition $atms\text{-}of\ C' \subseteq atms\text{-}of\text{-}ms\ N$ because to ensure that we can backjump even if the last decision variable has disappeared.

The part of the condition $atm\text{-}of\ L \in atm\text{-}of\ ' lits\text{-}of\ (F' @ Marked\ K\ () \# F)$ is important, otherwise you are not sure that you can backtrack.

14.3.1 Definition

We define $dp\text{ll}$ with backjumping:

inductive $dp\text{ll}\text{-}bj :: 'st \Rightarrow 'st \Rightarrow bool$ **for** $S :: 'st$ **where**

$bj\text{-}decide_{NOT}:$ $decide_{NOT}\ S\ S' \Longrightarrow dp\text{ll}\text{-}bj\ S\ S' \mid$

$bj\text{-}propagate_{NOT}:$ $propagate_{NOT}\ S\ S' \Longrightarrow dp\text{ll}\text{-}bj\ S\ S' \mid$

$bj\text{-}backjump:$ $backjump\ S\ S' \Longrightarrow dp\text{ll}\text{-}bj\ S\ S'$

lemmas $dp\text{ll}\text{-}bj\text{-}induct = dp\text{ll}\text{-}bj.induct[split\text{-}format(complete)]$

thm $dp\text{ll}\text{-}bj\text{-}induct[OF\ dp\text{ll}\text{-}with\text{-}backjumping\text{-}ops\text{-}axioms]$

lemma $dp\text{ll}\text{-}bj\text{-}all\text{-}induct[consumes\ 2,\ case\text{-}names\ decide_{NOT}\ propagate_{NOT}\ backjump]:$

fixes $S\ T :: 'st$

assumes

$dp\text{ll}\text{-}bj\ S\ T$ **and**

$inv\ S$

$\bigwedge L\ T. undefined\text{-}lit\ (trail\ S)\ L \Longrightarrow atm\text{-}of\ L \in atms\text{-}of\text{-}msu\ (clauses\ S)$

$\Longrightarrow T \sim prepend\text{-}trail\ (Marked\ L\ ())\ S$

$\Longrightarrow P\ S\ T$ **and**

$\bigwedge C\ L\ T. C + \{\#L\#\} \in \# clauses\ S \Longrightarrow trail\ S \models_{as} CNot\ C \Longrightarrow undefined\text{-}lit\ (trail\ S)\ L$

$\Longrightarrow T \sim prepend\text{-}trail\ (Propagated\ L\ ())\ S$

$\Longrightarrow P\ S\ T$ **and**

$\bigwedge C\ F'\ K\ F\ L\ C'\ T. C \in \# clauses\ S \Longrightarrow F' @ Marked\ K\ () \# F \models_{as} CNot\ C$

$\Longrightarrow trail\ S = F' @ Marked\ K\ () \# F$

$\Longrightarrow undefined\text{-}lit\ F\ L$

$\Longrightarrow atm\text{-}of\ L \in atms\text{-}of\text{-}msu\ (clauses\ S) \cup atm\text{-}of\ ' (lits\text{-}of\ (F' @ Marked\ K\ () \# F))$

$\Longrightarrow clauses\ S \models_{pm} C' + \{\#L\#\}$

$\Longrightarrow F \models_{as} CNot\ C'$

$\Longrightarrow T \sim prepend\text{-}trail\ (Propagated\ L\ ())\ (reduce\text{-}trail\text{-}to_{NOT}\ F\ S)$

$\Longrightarrow P\ S\ T$

shows $P\ S\ T$

apply $(induct\ T\ rule: dp\text{ll}\text{-}bj\text{-}induct[OF\ local.dp\text{ll}\text{-}with\text{-}backjumping\text{-}ops\text{-}axioms])$

apply $(rule\ assms(1))$

using *assms*(3) apply *blast*
 apply (*elim propagateE*) using *assms*(4) apply *blast*
 apply (*elim backjumpE*) using *assms*(5) $\langle \text{inv } S \rangle$ by *simp*

14.3.2 Basic properties

First, some better suited induction principle lemma *dpll-bj-clauses*:

assumes *dpll-bj* *S T* and *inv S*
 shows *clauses S = clauses T*
 using *assms* by (induction rule: *dpll-bj-all-induct*) auto

No duplicates in the trail lemma *dpll-bj-no-dup*:

assumes *dpll-bj* *S T* and *inv S*
 and *no-dup* (*trail S*)
 shows *no-dup* (*trail T*)
 using *assms* by (induction rule: *dpll-bj-all-induct*)
 (auto *simp add: defined-lit-map reduce-trail-to_{NOT}-skip-beginning*)

Valuations lemma *dpll-bj-sat-iff*:

assumes *dpll-bj* *S T* and *inv S*
 shows $I \models_{sm} \text{clauses } S \longleftrightarrow I \models_{sm} \text{clauses } T$
 using *assms* by (induction rule: *dpll-bj-all-induct*) auto

Clauses lemma *dpll-bj-atms-of-ms-clauses-inv*:

assumes
 dpll-bj *S T* and
 inv S
 shows *atms-of-msu* (*clauses S*) = *atms-of-msu* (*clauses T*)
 using *assms* by (induction rule: *dpll-bj-all-induct*) auto

lemma *dpll-bj-atms-in-trail*:

assumes
 dpll-bj *S T* and
 inv S and
 $\text{atm-of } ' (\text{lits-of } (\text{trail } S)) \subseteq \text{atms-of-msu } (\text{clauses } S)$
 shows $\text{atm-of } ' (\text{lits-of } (\text{trail } T)) \subseteq \text{atms-of-msu } (\text{clauses } S)$
 using *assms* by (induction rule: *dpll-bj-all-induct*)
 (auto *simp: in-plus-implies-atm-of-on-atms-of-ms reduce-trail-to_{NOT}-skip-beginning*)

lemma *dpll-bj-atms-in-trail-in-set*:

assumes *dpll-bj* *S T* and
 inv S and
 $\text{atms-of-msu } (\text{clauses } S) \subseteq A$ and
 $\text{atm-of } ' (\text{lits-of } (\text{trail } S)) \subseteq A$
 shows $\text{atm-of } ' (\text{lits-of } (\text{trail } T)) \subseteq A$
 using *assms* by (induction rule: *dpll-bj-all-induct*)
 (auto *simp: in-plus-implies-atm-of-on-atms-of-ms*)

lemma *dpll-bj-all-decomposition-implies-inv*:

assumes
 dpll-bj *S T* and
 inv: inv S and
 $\text{decomp: all-decomposition-implies-m } (\text{clauses } S) (\text{get-all-marked-decomposition } (\text{trail } S))$
 shows $\text{all-decomposition-implies-m } (\text{clauses } T) (\text{get-all-marked-decomposition } (\text{trail } T))$
 using *assms*(1,2)


```

proof (induction rule:dpll-bj-all-induct)
  case decideNOT
  then show ?case using decomp by auto
next
  case (propagateNOT C L T) note propa = this(1) and undef = this(3) and T = this(4)
  let ?M' = trail (prepend-trail (Propagated L ()) S)
  let ?N = clauses S
  obtain a y l where ay: get-all-marked-decomposition ?M' = (a, y) # l
    by (cases get-all-marked-decomposition ?M') fastforce+
  then have M': ?M' = y @ a using get-all-marked-decomposition-decomp[of ?M'] by auto
  have M: get-all-marked-decomposition (trail S) = (a, tl y) # l
    using ay undef by (cases get-all-marked-decomposition (trail S)) auto
  have y0: y = (Propagated L ()) # (tl y)
    using ay undef by (auto simp add: M)
  from arg-cong[OF this, of set] have y[simp]: set y = insert (Propagated L ()) (set (tl y))
    by simp
  have tr-S: trail S = tl y @ a
    using arg-cong[OF M', of tl] y0 M get-all-marked-decomposition-decomp by force
  have a-Un-N-M: (λa. {#lit-of a#}) ' set a ∪ set-mset ?N ⊢ps (λa. {#lit-of a#}) ' set (tl y)
    using decomp ay unfolding all-decomposition-implies-def by (simp add: M)+

moreover have (λa. {#lit-of a#}) ' set a ∪ set-mset ?N ⊢p {#L#} (is ?I ⊢p -)
proof (rule true-clss-clss-plus-CNot)
  show ?I ⊢p C + {#L#}
    using propa propagateNOT.prems by (auto dest!: true-clss-clss-in-imp-true-clss-clss)
next
  have (λm. {#lit-of m#}) ' set ?M' ⊢ps CNot C
    using (trail S ⊢as CNot C) undef by (auto simp add: true-annots-true-clss-clss)
  have a1: (λm. {#lit-of m#}) ' set a ∪ (λm. {#lit-of m#}) ' set (tl y) ⊢ps CNot C
    using propagateNOT.hyps(2) tr-S true-annots-true-clss-clss
    by (force simp add: image-Un sup-commute)
  have a2: set-mset (clauses S) ∪ (λa. {#lit-of a#}) ' set a
    ⊢ps (λa. {#lit-of a#}) ' set (tl y)
    using calculation by (auto simp add: sup-commute)
  show (λm. {#lit-of m#}) ' set a ∪ set-mset (clauses S) ⊢ps CNot C
    proof -
      have set-mset (clauses S) ∪ (λm. {#lit-of m#}) ' set a ⊢ps
        (λm. {#lit-of m#}) ' set a ∪ (λm. {#lit-of m#}) ' set (tl y)
        using a2 true-clss-clss-def by blast
      then show (λm. {#lit-of m#}) ' set a ∪ set-mset (clauses S) ⊢ps CNot C
        using a1 unfolding sup-commute by (meson true-clss-clss-left-right
          true-clss-clss-union-and true-clss-clss-union-l-r )
    qed
  qed

ultimately have (λa. {#lit-of a#}) ' set a ∪ set-mset ?N ⊢ps (λa. {#lit-of a#}) ' set ?M'
  unfolding M' by (auto simp add: all-in-true-clss-clss image-Un)

then show ?case
  using decomp T M undef unfolding ay all-decomposition-implies-def by (auto simp add: ay)
next
  case (backjump C F' K F L D T) note confl = this(2) and tr = this(3) and undef = this(4)
  and L = this(5) and N-C = this(6) and vars-D = this(5) and T = this(8)
  have decomp: all-decomposition-implies-m (clauses S) (get-all-marked-decomposition F)
    using decomp unfolding tr all-decomposition-implies-def

```

```

by (metis (no-types, lifting) get-all-marked-decomposition.simps(1)
    get-all-marked-decomposition-never-empty hd-Cons-tl insert-iff list.sel(3) list.set(2)
    tl-get-all-marked-decomposition-skip-some)

moreover have (λa. {#lit-of a#}) ‘ set (fst (hd (get-all-marked-decomposition F)))
  ∪ set-mset (clauses S)
  =ps (λa. {#lit-of a#}) ‘ set (snd (hd (get-all-marked-decomposition F)))
by (metis all-decomposition-implies-cons-single decomp get-all-marked-decomposition-never-empty
    hd-Cons-tl)
moreover
  have vars-of-D: atms-of D ⊆ atm-of ‘ lits-of F
    using ⟨F =as CNot D⟩ unfolding atms-of-def
    by (meson image-subsetI mem-set-mset-iff true-annots-CNot-all-atms-defined)

obtain a b li where F: get-all-marked-decomposition F = (a, b) # li
  by (cases get-all-marked-decomposition F) auto
have F = b @ a
  using get-all-marked-decomposition-decomp[of F a b] F by auto
have a-N-b:(λa. {#lit-of a#}) ‘ set a ∪ set-mset (clauses S) =ps (λa. {#lit-of a#}) ‘ set b
  using decomp unfolding all-decomposition-implies-def by (auto simp add: F)

have F-D:(λa. {#lit-of a#}) ‘ set F =ps CNot D
  using ⟨F =as CNot D⟩ by (simp add: true-annots-true-clss-clss)
then have (λa. {#lit-of a#}) ‘ set a ∪ (λa. {#lit-of a#}) ‘ set b =ps CNot D
  unfolding ⟨F = b @ a⟩ by (simp add: image-Un sup.commute)
have a-N-CNot-D: (λa. {#lit-of a#}) ‘ set a ∪ set-mset (clauses S)
  =ps CNot D ∪ (λa. {#lit-of a#}) ‘ set b
  apply (rule true-clss-clss-left-right)
  using a-N-b F-D unfolding ⟨F = b @ a⟩ by (auto simp add: image-Un ac-simps)

have a-N-D-L: (λa. {#lit-of a#}) ‘ set a ∪ set-mset (clauses S) =p D+{#L#}
  by (simp add: N-C)
have (λa. {#lit-of a#}) ‘ set a ∪ set-mset (clauses S) =p {#L#}
  using a-N-D-L a-N-CNot-D by (blast intro: true-clss-clss-plus-CNot)
then show ?case
  using decomp T tr undef unfolding all-decomposition-implies-def by (auto simp add: F)
qed

```

14.3.3 Termination

Using a proper measure lemma *length-get-all-marked-decomposition-append-Marked*:

```

length (get-all-marked-decomposition (F' @ Marked K () # F)) =
  length (get-all-marked-decomposition F')
  + length (get-all-marked-decomposition (Marked K () # F))
  - 1
by (induction F' rule: marked-lit-list-induct) auto

```

lemma *take-length-get-all-marked-decomposition-marked-sandwich*:

```

take (length (get-all-marked-decomposition F))
  (map (f o snd) (rev (get-all-marked-decomposition (F' @ Marked K () # F))))
=
  map (f o snd) (rev (get-all-marked-decomposition F))

```

proof (induction F' rule: marked-lit-list-induct)
 case nil
 then show ?case by auto

```

next
  case (marked K)
  then show ?case by (simp add: length-get-all-marked-decomposition-append-Marked)
next
  case (proped L m F') note IH = this(1)
  obtain a b l where F': get-all-marked-decomposition (F' @ Marked K () # F) = (a, b) # l
  by (cases get-all-marked-decomposition (F' @ Marked K () # F)) auto
  have length (get-all-marked-decomposition F) - length l = 0
  using length-get-all-marked-decomposition-append-Marked[of F' K F]
  unfolding F' by (cases get-all-marked-decomposition F') auto
  then show ?case
  using IH by (simp add: F')
qed

```

lemma *length-get-all-marked-decomposition-length:*
 $\text{length (get-all-marked-decomposition } M) \leq 1 + \text{length } M$
 by (induction M rule: marked-lit-list-induct) auto

lemma *length-in-get-all-marked-decomposition-bounded:*
 assumes $i: i \in \text{set (trail-weight } S)$
 shows $i \leq \text{Suc (length (trail } S))$
proof –
 obtain a b where
 $(a, b) \in \text{set (get-all-marked-decomposition (trail } S))$ and
 $ib: i = \text{Suc (length } b)$
 using i by auto
 then obtain c where $\text{trail } S = c @ b @ a$
 using get-all-marked-decomposition-exists-prepend' by metis
 from arg-cong[OF this, of length] show ?thesis using i ib by auto
qed

Well-foundedness The bounds are the following:

- $1 + \text{card (atms-of-ms } A)$: $\text{card (atms-of-ms } A)$ is an upper bound on the length of the list. As *get-all-marked-decomposition* appends an possibly empty couple at the end, adding one is needed.
- $2 + \text{card (atms-of-ms } A)$: $\text{card (atms-of-ms } A)$ is an upper bound on the number of elements, where adding one is necessary for the same reason as for the bound on the list, and one is needed to have a strict bound.

abbreviation *unassigned-lit* :: $'b \text{ literal multiset set} \Rightarrow 'a \text{ list} \Rightarrow \text{nat}$ **where**
 $\text{unassigned-lit } N M \equiv \text{card (atms-of-ms } N) - \text{length } M$

lemma *dpll-bj-trail-mes-increasing-prop:*
 fixes $M :: ('v, \text{unit}, \text{unit}) \text{ marked-lits}$ and $N :: 'v \text{ clauses}$
 assumes
 $\text{dpll-bj } S T$ and
 $\text{inv } S$ and
 $NA: \text{atms-of-msu (clauses } S) \subseteq \text{atms-of-ms } A$ and
 $MA: \text{atm-of ' lits-of (trail } S) \subseteq \text{atms-of-ms } A$ and
 $n\text{-d: no-dup (trail } S)$ and
 $\text{finite: finite } A$
 shows $\mu_C (1 + \text{card (atms-of-ms } A)) (2 + \text{card (atms-of-ms } A)) (\text{trail-weight } T)$
 $> \mu_C (1 + \text{card (atms-of-ms } A)) (2 + \text{card (atms-of-ms } A)) (\text{trail-weight } S)$

```

using assms(1,2)
proof (induction rule: dpll-bj-all-induct)
  case (propagateNOT C L) note CLN = this(1) and MC = this(2) and undef-L = this(3) and T =
this(4)
  have incl: atm-of ‘lits-of (Propagated L ()) # trail S) ⊆ atms-of-ms A
    using propagateNOT.hypos propagate-ops.propagateNOT dpll-bj-atms-in-trail-in-set bj-propagateNOT
    NA MA CLN by (auto simp: in-plus-implies-atm-of-on-atms-of-ms)

  have no-dup: no-dup (Propagated L ()) # trail S)
    using defined-lit-map n-d undef-L by auto
  obtain a b l where M: get-all-marked-decomposition (trail S) = (a, b) # l
    by (case-tac get-all-marked-decomposition (trail S)) auto
  have b-le-M: length b ≤ length (trail S)
    using get-all-marked-decomposition-decomp[of trail S] by (simp add: M)
  have finite (atms-of-ms A) using finite by simp

  then have length (Propagated L ()) # trail S) ≤ card (atms-of-ms A)
    using incl finite unfolding no-dup-length-eq-card-atm-of-lits-of[OF no-dup]
    by (simp add: card-mono)
  then have latm: unassigned-lit A b = Suc (unassigned-lit A (Propagated L d # b))
    using b-le-M by auto
  then show ?case using T undef-L by (auto simp: latm M μC-cons)
next
  case (decideNOT L) note undef-L = this(1) and MC = this(2) and T = this(3)
  have incl: atm-of ‘lits-of (Marked L ()) # (trail S)) ⊆ atms-of-ms A
    using dpll-bj-atms-in-trail-in-set bj-decideNOT decideNOT.decideNOT[OF decideNOT.hypos] NA MA
MC
    by auto

  have no-dup: no-dup (Marked L ()) # (trail S))
    using defined-lit-map n-d undef-L by auto
  obtain a b l where M: get-all-marked-decomposition (trail S) = (a, b) # l
    by (case-tac get-all-marked-decomposition (trail S)) auto

  then have length (Marked L ()) # (trail S)) ≤ card (atms-of-ms A)
    using incl finite unfolding no-dup-length-eq-card-atm-of-lits-of[OF no-dup]
    by (simp add: card-mono)
  then have latm: unassigned-lit A (trail S) = Suc (unassigned-lit A (Marked L lv # (trail S))))
    by force
  show ?case using T undef-L by (simp add: latm μC-cons)
next
  case (backjump C F' K F L C' T) note undef-L = this(4) and MC = this(1) and tr-S = this(3)
and
  L = this(5) and T = this(8)
  have incl: atm-of ‘lits-of (Propagated L ()) # F) ⊆ atms-of-ms A
    using dpll-bj-atms-in-trail-in-set NA MA tr-S L by auto

  have no-dup: no-dup (Propagated L ()) # F)
    using defined-lit-map n-d undef-L tr-S by auto
  obtain a b l where M: get-all-marked-decomposition (trail S) = (a, b) # l
    by (cases get-all-marked-decomposition (trail S)) auto
  have b-le-M: length b ≤ length (trail S)
    using get-all-marked-decomposition-decomp[of trail S] by (simp add: M)
  have fin-atms-A: finite (atms-of-ms A) using finite by simp

```

then have $F\text{-le-}A$: $\text{length } (\text{Propagated } L \ () \# F) \leq \text{card } (\text{atms-of-}ms \ A)$
using *incl finite unfolding no-dup-length-eq-card-atm-of-lits-of*[*OF no-dup*]
by (*simp add: card-mono*)
have $tr\text{-}S\text{-le-}A$: $\text{length } (\text{trail } S) \leq (\text{card } (\text{atms-of-}ms \ A))$
using *n-d MA by (metis fin-atms-A card-mono no-dup-length-eq-card-atm-of-lits-of)*
obtain $a \ b \ l$ **where** F : *get-all-marked-decomposition* $F = (a, b) \# l$
by (*cases get-all-marked-decomposition F*) *auto*
then have $F = b @ a$
using *get-all-marked-decomposition-decomp*[*of Propagated L () # F a*
Propagated L () # b] **by** *simp*
then have $latm$: *unassigned-lit A b = Suc (unassigned-lit A (Propagated L () # b))*
using $F\text{-le-}A$ **by** *simp*
obtain rem **where**
 rem : *map* $(\lambda a. \text{Suc } (\text{length } (\text{snd } a)))$ $(\text{rev } (\text{get-all-marked-decomposition } (F' @ \text{Marked } K \ () \# F)))$
 $= \text{map } (\lambda a. \text{Suc } (\text{length } (\text{snd } a)))$ $(\text{rev } (\text{get-all-marked-decomposition } F)) @ rem$
using *take-length-get-all-marked-decomposition-marked-sandwich*[*of F* $\lambda a. \text{Suc } (\text{length } a)$ $F' \ K$]
unfolding *o-def* **by** (*metis append-take-drop-id*)
then have rem : *map* $(\lambda a. \text{Suc } (\text{length } (\text{snd } a)))$
 $(\text{get-all-marked-decomposition } (F' @ \text{Marked } K \ () \# F))$
 $= \text{rev } rem @ \text{map } (\lambda a. \text{Suc } (\text{length } (\text{snd } a)))$ $((\text{get-all-marked-decomposition } F))$
by (*simp add: rev-map[symmetric] rev-swap*)
have $\text{length } (\text{rev } rem @ \text{map } (\lambda a. \text{Suc } (\text{length } (\text{snd } a)))$ $(\text{get-all-marked-decomposition } F))$
 $\leq \text{Suc } (\text{card } (\text{atms-of-}ms \ A))$
using *arg-cong*[*OF rem, of length*] $tr\text{-}S\text{-le-}A$
 $\text{length-get-all-marked-decomposition-length}$ [*of F' @ Marked K () # F*] $tr\text{-}S$ **by** *auto*
moreover
{ **fix** $i :: nat$ **and** $xs :: 'a \text{ list}$
have $i < \text{length } xs \implies \text{length } xs - \text{Suc } i < \text{length } xs$
by *auto*
then have H : $i < \text{length } xs \implies \text{rev } xs ! i \in \text{set } xs$
using *rev-nth*[*of i xs*] **unfolding** *in-set-conv-nth* **by** (*force simp add: in-set-conv-nth*)
} **note** $H = \text{this}$
have $\forall i < \text{length } rem. \text{rev } rem ! i < \text{card } (\text{atms-of-}ms \ A) + 2$
using $tr\text{-}S\text{-le-}A$ *length-in-get-all-marked-decomposition-bounded*[*of - S*] **unfolding** $tr\text{-}S$
by (*force simp add: o-def rem dest!: H intro: length-get-all-marked-decomposition-length*)
ultimately show *?case*
using $\mu_C\text{-bounded}$ [*of rev rem card (atms-of-}ms \ A)+2* *unassigned-lit A l*] $T \text{ undef-}L$
by (*simp add: rem μ_C -append μ_C -cons F tr-S*)
qed

lemma *dpll-bj-trail-mes-decreasing-prop*:

assumes $dpll$: $dpll\text{-}bj \ S \ T$ **and** inv : $inv \ S$ **and**
 $N\text{-}A$: $\text{atms-of-}msu \ (\text{clauses } S) \subseteq \text{atms-of-}ms \ A$ **and**
 $M\text{-}A$: $\text{atm-of } ' \text{ lits-of } (\text{trail } S) \subseteq \text{atms-of-}ms \ A$ **and**
 nd : *no-dup* $(\text{trail } S)$ **and**
 $fin\text{-}A$: *finite A*

shows $(2 + \text{card } (\text{atms-of-}ms \ A)) \wedge (1 + \text{card } (\text{atms-of-}ms \ A))$
 $- \mu_C \ (1 + \text{card } (\text{atms-of-}ms \ A)) \ (2 + \text{card } (\text{atms-of-}ms \ A)) \ (\text{trail-weight } T)$
 $< (2 + \text{card } (\text{atms-of-}ms \ A)) \wedge (1 + \text{card } (\text{atms-of-}ms \ A))$
 $- \mu_C \ (1 + \text{card } (\text{atms-of-}ms \ A)) \ (2 + \text{card } (\text{atms-of-}ms \ A)) \ (\text{trail-weight } S)$

proof –

let $?b = 2 + \text{card } (\text{atms-of-}ms \ A)$
let $?s = 1 + \text{card } (\text{atms-of-}ms \ A)$
let $? \mu = \mu_C \ ?s \ ?b$
have $M'\text{-}A$: $\text{atm-of } ' \text{ lits-of } (\text{trail } T) \subseteq \text{atms-of-}ms \ A$

```

  by (meson M-A N-A dpll dpll-bj-atms-in-trail-in-set inv)
have nd': no-dup (trail T)
  using ⟨dpll-bj S T⟩ dpll-bj-no-dup nd inv by blast
{ fix i :: nat and xs :: 'a list
  have i < length xs  $\implies$  length xs - Suc i < length xs
    by auto
  then have H: i < length xs  $\implies$  xs ! i  $\in$  set xs
    using rev-nth[of i xs] unfolding in-set-conv-nth by (force simp add: in-set-conv-nth)
} note H = this

have l-M-A: length (trail S)  $\leq$  card (atms-of-ms A)
  by (simp add: fin-A M-A card-mono no-dup-length-eq-card-atm-of-lits-of nd)
have l-M'-A: length (trail T)  $\leq$  card (atms-of-ms A)
  by (simp add: fin-A M'-A card-mono no-dup-length-eq-card-atm-of-lits-of nd')
have l-trail-weight-M: length (trail-weight T)  $\leq$  1 + card (atms-of-ms A)
  using l-M'-A length-get-all-marked-decomposition-length[of trail T] by auto
have bounded-M:  $\forall i < \text{length } (\text{trail-weight } T). (\text{trail-weight } T)! i < \text{card } (\text{atms-of-ms } A) + 2$ 
  using length-in-get-all-marked-decomposition-bounded[of - T] l-M'-A
  by (metis (no-types, lifting) Nat.le-trans One-nat-def Suc-1 add.right-neutral add-Suc-right
    le-imp-less-Suc less-eq-Suc-le nth-mem)

from dpll-bj-trail-mes-increasing-prop[OF dpll inv N-A M-A nd fin-A]
have  $\mu_C \text{ ?s ?b } (\text{trail-weight } S) < \mu_C \text{ ?s ?b } (\text{trail-weight } T)$  by simp
moreover from  $\mu_C$ -bounded[OF bounded-M l-trail-weight-M]
  have  $\mu_C \text{ ?s ?b } (\text{trail-weight } T) \leq \text{?b} \wedge \text{?s}$  by auto
ultimately show ?thesis by linarith
qed

```

lemma wf-dpll-bj:

```

  assumes fin: finite A
  shows wf {(T, S). dpll-bj S T
     $\wedge$  atms-of-msu (clauses S)  $\subseteq$  atms-of-ms A  $\wedge$  atm-of ' lits-of (trail S)  $\subseteq$  atms-of-ms A
     $\wedge$  no-dup (trail S)  $\wedge$  inv S}
  (is wf ?A)
proof (rule wf-bounded-measure[of -
   $\lambda \cdot. (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$ 
   $\lambda S. \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } S)]$ )
  fix a b :: 'st
  let ?b = 2 + card (atms-of-ms A)
  let ?s = 1 + card (atms-of-ms A)
  let ? $\mu$  =  $\mu_C \text{ ?s ?b}$ 
  assume ab: (b, a)  $\in$  {(T, S). dpll-bj S T
     $\wedge$  atms-of-msu (clauses S)  $\subseteq$  atms-of-ms A  $\wedge$  atm-of ' lits-of (trail S)  $\subseteq$  atms-of-ms A
     $\wedge$  no-dup (trail S)  $\wedge$  inv S}
  have fin-A: finite (atms-of-ms A)
    using fin by auto
  have
    dpll-bj: dpll-bj a b and
    N-A: atms-of-msu (clauses a)  $\subseteq$  atms-of-ms A and
    M-A: atm-of ' lits-of (trail a)  $\subseteq$  atms-of-ms A and
    nd: no-dup (trail a) and
    inv: inv a
    using ab by auto

```

```

have M'-A: atm-of ' lits-of (trail b)  $\subseteq$  atms-of-ms A
  by (meson M-A N-A  $\langle$  dpll-bj a b  $\rangle$  dpll-bj-atms-in-trail-in-set inv)
have nd': no-dup (trail b)
  using  $\langle$  dpll-bj a b  $\rangle$  dpll-bj-no-dup nd inv by blast
{ fix i :: nat and xs :: 'a list
  have i < length xs  $\implies$  length xs - Suc i < length xs
    by auto
  then have H: i < length xs  $\implies$  xs ! i  $\in$  set xs
    using rev-nth[of i xs] unfolding in-set-conv-nth by (force simp add: in-set-conv-nth)
} note H = this

have l-M-A: length (trail a)  $\leq$  card (atms-of-ms A)
  by (simp add: fin-A M-A card-mono no-dup-length-eq-card-atm-of-lits-of nd)
have l-M'-A: length (trail b)  $\leq$  card (atms-of-ms A)
  by (simp add: fin-A M'-A card-mono no-dup-length-eq-card-atm-of-lits-of nd')
have l-trail-weight-M: length (trail-weight b)  $\leq$  1 + card (atms-of-ms A)
  using l-M'-A length-get-all-marked-decomposition-length[of trail b] by auto
have bounded-M:  $\forall i < \text{length } (\text{trail-weight } b). (\text{trail-weight } b) ! i < \text{card } (\text{atms-of-ms } A) + 2$ 
  using length-in-get-all-marked-decomposition-bounded[of - b] l-M'-A
  by (metis (no-types, lifting) Nat.le-trans One-nat-def Suc-1 add.right-neutral add-Suc-right
    le-imp-less-Suc less-eq-Suc-le nth-mem)

from dpll-bj-trail-mes-increasing-prop[OF dpll-bj inv N-A M-A nd fin]
have  $\mu_C \text{ ?s ?b } (\text{trail-weight } a) < \mu_C \text{ ?s ?b } (\text{trail-weight } b)$  by simp
moreover from  $\mu_C$ -bounded[OF bounded-M l-trail-weight-M]
  have  $\mu_C \text{ ?s ?b } (\text{trail-weight } b) \leq \text{?b} \wedge \text{?s}$  by auto
ultimately show  $\text{?b} \wedge \text{?s} \leq \text{?b} \wedge \text{?s} \wedge$ 
   $\mu_C \text{ ?s ?b } (\text{trail-weight } b) \leq \text{?b} \wedge \text{?s} \wedge$ 
   $\mu_C \text{ ?s ?b } (\text{trail-weight } a) < \mu_C \text{ ?s ?b } (\text{trail-weight } b)$ 
  by blast
qed

```

14.3.4 Normal Forms

We prove that given a normal form of DPLL, with some invariants, the either N is satisfiable and the built valuation M is a model; or N is unsatisfiable.

Idea of the proof: We have to prove that *satisfiable* N , $\neg M \models_{as} N$ and there is no remaining step is incompatible.

1. The *decide* rules tells us that every variable in N has a value.
2. $\neg M \models_{as} N$ tells us that there is conflict.
3. There is at least one decision in the trail (otherwise, M is a model of N).
4. Now if we build the clause with all the decision literals of the trail, we can apply the *backjump* rule.

The assumption are saying that we have a finite upper bound A for the literals, that we cannot do any step *no-step dpll-bj* S

theorem *dpll-backjump-final-state*:

```

fixes A :: 'v literal multiset set and S T :: 'st
assumes
  atms-of-msu (clauses S)  $\subseteq$  atms-of-ms A and

```

```

atm-of ' lits-of (trail S)  $\subseteq$  atms-of-ms A and
no-dup (trail S) and
finite A and
inv: inv S and
n-s: no-step dpll-bj S and
decomp: all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S))
shows unsatisfiable (set-mset (clauses S))
   $\vee$  (trail S  $\models_{asm}$  clauses S  $\wedge$  satisfiable (set-mset (clauses S)))
proof -
let ?N = set-mset (clauses S)
let ?M = trail S
consider
  (sat) satisfiable ?N and ?M  $\models_{as}$  ?N
| (sat') satisfiable ?N and  $\neg$  ?M  $\models_{as}$  ?N
| (unsat) unsatisfiable ?N
by auto
then show ?thesis
proof cases
case sat' note sat = this(1) and M = this(2)
obtain C where C  $\in$  ?N and  $\neg$  ?M  $\models_a$  C using M unfolding true-annots-def by auto
obtain I :: 'v literal set where
  I  $\models_s$  ?N and
  cons: consistent-interp I and
  tot: total-over-m I ?N and
  atm-I-N: atm-of ' I  $\subseteq$  atms-of-ms ?N
  using sat unfolding satisfiable-def-min by auto
let ?I = I  $\cup$  {P | P. P  $\in$  lits-of ?M  $\wedge$  atm-of P  $\notin$  atm-of ' I}
let ?O = {{#lit-of L#} | L. is-marked L  $\wedge$  L  $\in$  set ?M  $\wedge$  atm-of (lit-of L)  $\notin$  atms-of-ms ?N}
have cons-I': consistent-interp ?I
  using cons using (no-dup ?M) unfolding consistent-interp-def
  by (auto simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set lits-of-def
    dest!: no-dup-cannot-not-lit-and-uminus)
have tot-I': total-over-m ?I (?N  $\cup$  ( $\lambda a.$  {#lit-of a#}) ' set ?M)
  using tot atms-of-s-def unfolding total-over-m-def total-over-set-def
  by fastforce
have {P | P. P  $\in$  lits-of ?M  $\wedge$  atm-of P  $\notin$  atm-of ' I}  $\models_s$  ?O
  using (I  $\models_s$  ?N) atm-I-N by (auto simp add: atm-of-eq-atm-of true-clss-def lits-of-def)
then have I'-N: ?I  $\models_s$  ?N  $\cup$  ?O
  using (I  $\models_s$  ?N) true-clss-union-increase by force
have tot': total-over-m ?I (?N  $\cup$  ?O)
  using atm-I-N tot unfolding total-over-m-def total-over-set-def
  by (force simp: image-iff lits-of-def dest!: is-marked-ex-Marked)

have atms-N-M: atms-of-ms ?N  $\subseteq$  atm-of ' lits-of ?M
proof (rule ccontr)
assume  $\neg$  ?thesis
then obtain l :: 'v where
  l-N: l  $\in$  atms-of-ms ?N and
  l-M: l  $\notin$  atm-of ' lits-of ?M
  by auto
have undefined-lit ?M (Pos l)
  using l-M by (metis Marked-Propagated-in-iff-in-lits-of
    atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set literal.sel(1))
from bj-decideNOT[OF decideNOT[OF this]] show False
  using l-N n-s by (metis literal.sel(1) state-eqNOT-ref)

```


qed

have $?M \models_{as} CNot\ C$
 by (metis $\langle C \in set\ mset\ (clauses\ S) \rangle \langle \neg\ trail\ S \models_a\ C \rangle$ all-variables-defined-not-imply-cnot
 atms-N-M atms-of-atms-of-ms-mono atms-of-ms-CNot-atms-of atms-of-ms-CNot-atms-of-ms
 subset-eq)
 have $\exists l \in set\ ?M. is\ marked\ l$
 proof (rule ccontr)
 let $?O = \{\{\#lit\ of\ L\#\} \mid L. is\ marked\ L \wedge L \in set\ ?M \wedge atm\ of\ (lit\ of\ L) \notin atms\ of\ ms\ ?N\}$
 have $\vartheta[i\!ff]: \bigwedge I. total\ over\ m\ I\ (?N \cup ?O \cup (\lambda a. \{\#lit\ of\ a\#\})) \text{ ‘ } set\ ?M$
 $\longleftrightarrow total\ over\ m\ I\ (?N \cup (\lambda a. \{\#lit\ of\ a\#\})) \text{ ‘ } set\ ?M$
 unfolding total-over-set-def total-over-m-def atms-of-ms-def by auto
 assume $\neg\ ?thesis$
 then have [simp]: $\{\{\#lit\ of\ L\#\} \mid L. is\ marked\ L \wedge L \in set\ ?M\}$
 $= \{\{\#lit\ of\ L\#\} \mid L. is\ marked\ L \wedge L \in set\ ?M \wedge atm\ of\ (lit\ of\ L) \notin atms\ of\ ms\ ?N\}$
 by auto
 then have $?N \cup ?O \models_{ps} (\lambda a. \{\#lit\ of\ a\#\}) \text{ ‘ } set\ ?M$
 using all-decomposition-implies-propagated-lits-are-implied[OF decomp] by auto

 then have $?I \models_s (\lambda a. \{\#lit\ of\ a\#\}) \text{ ‘ } set\ ?M$
 using cons-I' I'-N tot-I' $\langle I \models_s ?N \cup ?O \rangle$ unfolding ϑ true-clss-clss-def by blast
 then have $lits\ of\ ?M \subseteq ?I$
 unfolding true-clss-def lits-of-def by auto
 then have $?M \models_{as} ?N$
 using I'-N $\langle C \in ?N \rangle \langle \neg\ ?M \models_a\ C \rangle$ cons-I' atms-N-M
 by (meson $\langle trail\ S \models_{as}\ CNot\ C \rangle$ consistent-CNot-not rev-subsetD sup-ge1 true-annot-def
 true-annots-def true-clss-mono-set-mset-l true-clss-def)
 then show False using M by fast
 qed
 from List.split-list-first-propE[OF this] obtain $K :: 'v\ literal\ and$
 $F\ F' :: ('v, unit, unit)\ marked\ lit\ list$ where
 $M\text{-}K: ?M = F' @ Marked\ K\ () \# F$ and
 $nm: \forall f \in set\ F'. \neg is\ marked\ f$
 unfolding is-marked-def by (metis (full-types) old.unit.exhaust)
 let $?K = Marked\ K\ () :: ('v, unit, unit)\ marked\ lit$
 have $?K \in set\ ?M$
 unfolding M-K by auto
 let $?C = image\ mset\ lit\ of\ \{\#L \in \#mset\ ?M. is\ marked\ L \wedge L \neq ?K\#\} :: 'v\ literal\ multiset$
 let $?C' = set\ mset\ (image\ mset\ (\lambda L :: 'v\ literal. \{\#L\#\})\ (?C + \{\#lit\ of\ ?K\#\}))$
 have $?N \cup \{\{\#lit\ of\ L\#\} \mid L. is\ marked\ L \wedge L \in set\ ?M\} \models_{ps} (\lambda a. \{\#lit\ of\ a\#\}) \text{ ‘ } set\ ?M$
 using all-decomposition-implies-propagated-lits-are-implied[OF decomp] .
 moreover have $C': ?C' = \{\{\#lit\ of\ L\#\} \mid L. is\ marked\ L \wedge L \in set\ ?M\}$
 unfolding M-K apply standard
 apply force
 using IntI by auto
 ultimately have $N\text{-}C\text{-}M: ?N \cup ?C' \models_{ps} (\lambda a. \{\#lit\ of\ a\#\}) \text{ ‘ } set\ ?M$
 by auto
 have $N\text{-}M\text{-}False: ?N \cup (\lambda L. \{\#lit\ of\ L\#\}) \text{ ‘ } (set\ ?M) \models_{ps} \{\{\#\}\}$
 using M $\langle ?M \models_{as}\ CNot\ C \rangle \langle C \in ?N \rangle$ unfolding true-clss-clss-def true-annots-def Ball-def
 true-annot-def by (metis consistent-CNot-not sup.orderE sup-commute true-clss-def
 true-clss-singleton-lit-of-implies-incl true-clss-union true-clss-union-increase)

 have undefined-lit F K using $\langle no\ dup\ ?M \rangle$ unfolding M-K by (simp add: defined-lit-map)
 moreover
 have $?N \cup ?C' \models_{ps} \{\{\#\}\}$

```

proof -
  have A: ?N  $\cup$  ?C'  $\cup$  ( $\lambda a. \{\# \text{lit-of } a \#\}$ ) ' set ?M =
    ?N  $\cup$  ( $\lambda a. \{\# \text{lit-of } a \#\}$ ) ' set ?M
    unfolding M-K by auto
  show ?thesis
    using true-clss-clss-left-right[OF N-C-M, of  $\{\{\#\}\}$ ] N-M-False unfolding A by auto
qed
have ?N  $\models_p$  image-mset uminus ?C +  $\{\# - K \#\}$ 
  unfolding true-clss-clss-def true-clss-clss-def total-over-m-def
proof (intro allI impI)
  fix I
  assume
    tot: total-over-set I (atms-of-ms (?N  $\cup$   $\{\text{image-mset uminus ?C} + \{\# - K \#\}\}$ )) and
    cons: consistent-interp I and
    I  $\models_s$  ?N
  have (K  $\in$  I  $\wedge$   $-K \notin$  I)  $\vee$  ( $-K \in$  I  $\wedge$  K  $\notin$  I)
    using cons tot unfolding consistent-interp-def by (cases K) auto
  have tot': total-over-set I
    (atm-of ' lit-of ' (set ?M  $\cap$   $\{L. \text{is-marked } L \wedge L \neq \text{Marked } K ()\}$ ))
    using tot by (auto simp add: atms-of-uminus-lit-atm-of-lit-of)
  { fix x :: ('v, unit, unit) marked-lit
    assume
      a3: lit-of x  $\notin$  I and
      a1: x  $\in$  set ?M and
      a4: is-marked x and
      a5: x  $\neq$  Marked K ()
    then have Pos (atm-of (lit-of x))  $\in$  I  $\vee$  Neg (atm-of (lit-of x))  $\in$  I
      using a5 a4 tot' a1 unfolding total-over-set-def atms-of-s-def by blast
    moreover have f6: Neg (atm-of (lit-of x)) =  $-$  Pos (atm-of (lit-of x))
      by simp
    ultimately have - lit-of x  $\in$  I
      using f6 a3 by (metis (no-types) atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
        literal.sel(1))
  } note H = this

  have  $\neg I \models_s$  ?C'
    using  $\langle ?N \cup ?C' \models_{ps} \{\{\#\}\} \rangle$  tot cons (I  $\models_s$  ?N)
    unfolding true-clss-clss-def total-over-m-def
    by (simp add: atms-of-uminus-lit-atm-of-lit-of atms-of-ms-single-image-atm-of-lit-of)
  then show I  $\models$  image-mset uminus ?C +  $\{\# - K \#\}$ 
    unfolding true-clss-def true-clss-def Bex-mset-def
    using  $\langle (K \in I \wedge -K \notin I) \vee (-K \in I \wedge K \notin I) \rangle$ 
    by (auto dest!: H)
qed
moreover have F  $\models_{as}$  CNot (image-mset uminus ?C)
  using nm unfolding true-annots-def CNot-def M-K by (auto simp add: lits-of-def)
ultimately have False
  using bj-can-jump[of S F' K F C  $-K$ 
    image-mset uminus (image-mset lit-of  $\{\# L : \# \text{ mset ?M. is-marked } L \wedge L \neq \text{Marked } K () \#\}$ )]
     $\langle C \in ?N \rangle$  n-s  $\langle ?M \models_{as} \text{CNot } C \rangle$  bj-backjump inv (no-dup (trail S)) unfolding M-K by auto
  then show ?thesis by fast
qed auto
qed
end

```

```

locale dpll-with-backjumping =
  dpll-with-backjumping-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
  propagate-conds inv backjump-conds
for
  trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
  clauses :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and tl-trail :: 'st  $\Rightarrow$  'st and
  add-clNOT remove-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  propagate-conds :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  bool and
  inv :: 'st  $\Rightarrow$  bool and
  backjump-conds :: 'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool
+
assumes dpll-bj-inv:  $\bigwedge S T. \text{dpll-bj } S T \Longrightarrow \text{inv } S \Longrightarrow \text{inv } T$ 
begin

lemma rtranclp-dpll-bj-inv:
assumes dpll-bj* S T and inv S
shows inv T
using assms by (induction rule: rtranclp-induct)
  (auto simp add: dpll-bj-no-dup intro: dpll-bj-inv)

lemma rtranclp-dpll-bj-no-dup:
assumes dpll-bj* S T and inv S
and no-dup (trail S)
shows no-dup (trail T)
using assms by (induction rule: rtranclp-induct)
  (auto simp add: dpll-bj-no-dup dest: rtranclp-dpll-bj-inv dpll-bj-inv)

lemma rtranclp-dpll-bj-atms-of-ms-clauses-inv:
assumes
  dpll-bj* S T and inv S
shows atms-of-msu (clauses S) = atms-of-msu (clauses T)
using assms by (induction rule: rtranclp-induct)
  (auto dest: rtranclp-dpll-bj-inv dpll-bj-atms-of-ms-clauses-inv)

lemma rtranclp-dpll-bj-atms-in-trail:
assumes
  dpll-bj* S T and
  inv S and
  atm-of ' (lits-of (trail S))  $\subseteq$  atms-of-msu (clauses S)
shows atm-of ' (lits-of (trail T))  $\subseteq$  atms-of-msu (clauses T)
using assms apply (induction rule: rtranclp-induct)
using dpll-bj-atms-in-trail dpll-bj-atms-of-ms-clauses-inv rtranclp-dpll-bj-inv by auto

lemma rtranclp-dpll-bj-sat-iff:
assumes dpll-bj* S T and inv S
shows I  $\models_{sm}$  clauses S  $\longleftrightarrow$  I  $\models_{sm}$  clauses T
using assms by (induction rule: rtranclp-induct)
  (auto dest!: dpll-bj-sat-iff simp: rtranclp-dpll-bj-inv)

lemma rtranclp-dpll-bj-atms-in-trail-in-set:
assumes
  dpll-bj* S T and
  inv S

```

$atms\text{-}of\text{-}msu\ (clauses\ S) \subseteq A$ **and**
 $atm\text{-}of\ ' (lits\text{-}of\ (trail\ S)) \subseteq A$
shows $atm\text{-}of\ ' (lits\text{-}of\ (trail\ T)) \subseteq A$
using *assms*
by (*induction rule: rtranclp-induct*)
 (*auto dest: rtranclp-dpll-bj-inv*
simp add: dpll-bj-atms-in-trail-in-set rtranclp-dpll-bj-atms-of-ms-clauses-inv
rtranclp-dpll-bj-inv)

lemma *rtranclp-dpll-bj-all-decomposition-implies-inv:*

assumes
 $dpll\text{-}bj^{**}\ S\ T$ **and**
 $inv\ S$
 $all\text{-}decomposition\text{-}implies\text{-}m\ (clauses\ S)\ (get\text{-}all\text{-}marked\text{-}decomposition\ (trail\ S))$
shows $all\text{-}decomposition\text{-}implies\text{-}m\ (clauses\ T)\ (get\text{-}all\text{-}marked\text{-}decomposition\ (trail\ T))$
using *assms* **by** (*induction rule: rtranclp-induct*)
 (*auto intro: dpll-bj-all-decomposition-implies-inv simp: rtranclp-dpll-bj-inv*)

lemma *rtranclp-dpll-bj-inv-incl-dpll-bj-inv-trancl:*

$\{(T, S). dpll\text{-}bj^{++}\ S\ T$
 $\wedge\ atms\text{-}of\text{-}msu\ (clauses\ S) \subseteq atms\text{-}of\text{-}ms\ A \wedge atm\text{-}of\ ' lits\text{-}of\ (trail\ S) \subseteq atms\text{-}of\text{-}ms\ A$
 $\wedge\ no\text{-}dup\ (trail\ S) \wedge inv\ S\}$
 $\subseteq \{(T, S). dpll\text{-}bj\ S\ T \wedge atms\text{-}of\text{-}msu\ (clauses\ S) \subseteq atms\text{-}of\text{-}ms\ A$
 $\wedge\ atm\text{-}of\ ' lits\text{-}of\ (trail\ S) \subseteq atms\text{-}of\text{-}ms\ A \wedge no\text{-}dup\ (trail\ S) \wedge inv\ S\}^+$
 (**is** $?A \subseteq ?B^+$)

proof *standard*

fix x
assume $x\text{-}A: x \in ?A$
obtain $S\ T::'st$ **where**
 $x[simp]: x = (T, S)$ **by** (*cases x*) *auto*
have
 $dpll\text{-}bj^{++}\ S\ T$ **and**
 $atms\text{-}of\text{-}msu\ (clauses\ S) \subseteq atms\text{-}of\text{-}ms\ A$ **and**
 $atm\text{-}of\ ' lits\text{-}of\ (trail\ S) \subseteq atms\text{-}of\text{-}ms\ A$ **and**
 $no\text{-}dup\ (trail\ S)$ **and**
 $inv\ S$
using $x\text{-}A$ **by** *auto*
then show $x \in ?B^+$ **unfolding** x
proof (*induction rule: tranclp-induct*)
case *base*
then show $?case$ **by** *auto*
next
case (*step* $T\ U$) **note** $step = this(1)$ **and** $ST = this(2)$ **and** $IH = this(3)[OF\ this(4-7)]$
and $N\text{-}A = this(4)$ **and** $M\text{-}A = this(5)$ **and** $nd = this(6)$ **and** $inv = this(7)$

have $[simp]: atms\text{-}of\text{-}msu\ (clauses\ S) = atms\text{-}of\text{-}msu\ (clauses\ T)$
using *step* $rtranclp\text{-}dpll\text{-}bj\text{-}atms\text{-}of\text{-}ms\text{-}clauses\text{-}inv\ tranclp\text{-}into\text{-}rtranclp\ inv$ **by** *fastforce*
have $no\text{-}dup\ (trail\ T)$
using *local.step nd rtranclp-dpll-bj-no-dup tranclp-into-rtranclp inv* **by** *fastforce*
moreover have $atm\text{-}of\ ' (lits\text{-}of\ (trail\ T)) \subseteq atms\text{-}of\text{-}ms\ A$
by (*metis inv M-A N-A local.step rtranclp-dpll-bj-atms-in-trail-in-set*
tranclp-into-rtranclp)
moreover have $inv\ T$
using *inv local.step rtranclp-dpll-bj-inv tranclp-into-rtranclp* **by** *fastforce*
ultimately have $(U, T) \in ?B$ **using** $ST\ N\text{-}A\ M\text{-}A\ inv$ **by** *auto*

then show ?case using IH by (rule trancl-into-trancl2)
qed
qed

lemma wf-tranclp-dpll-bj:
assumes fin: finite A
shows wf {(T, S). dpll-bj⁺⁺ S T
 \wedge atms-of-msu (clauses S) \subseteq atms-of-ms A \wedge atm-of ' lits-of (trail S) \subseteq atms-of-ms A
 \wedge no-dup (trail S) \wedge inv S}
using wf-trancl[OF wf-dpll-bj[OF fin]] rtranclp-dpll-bj-inv-incl-dpll-bj-inv-trancl
by (rule wf-subset)

lemma dpll-bj-sat-ext-iff:
dpll-bj S T \implies inv S \implies I|=sextm clauses S \longleftrightarrow I|=sextm clauses T
by (simp add: dpll-bj-clauses)

lemma rtranclp-dpll-bj-sat-ext-iff:
dpll-bj^{**} S T \implies inv S \implies I|=sextm clauses S \longleftrightarrow I|=sextm clauses T
by (induction rule: rtranclp-induct) (simp-all add: rtranclp-dpll-bj-inv dpll-bj-sat-ext-iff)

theorem full-dpll-backjump-final-state:
fixes A :: 'v literal multiset set **and** S T :: 'st
assumes
full: full dpll-bj S T **and**
atms-S: atms-of-msu (clauses S) \subseteq atms-of-ms A **and**
atms-trail: atm-of ' lits-of (trail S) \subseteq atms-of-ms A **and**
n-d: no-dup (trail S) **and**
finite A **and**
inv: inv S **and**
decomp: all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S))
shows unsatisfiable (set-mset (clauses S))
 \vee (trail T \models asm clauses S \wedge satisfiable (set-mset (clauses S)))

proof –
have st: dpll-bj^{**} S T **and** no-step dpll-bj T
using full **unfolding** full-def **by** fast+
moreover have atms-of-msu (clauses T) \subseteq atms-of-ms A
using atms-S inv rtranclp-dpll-bj-atms-of-ms-clauses-inv st **by** blast
moreover have atm-of ' lits-of (trail T) \subseteq atms-of-ms A
using atms-S atms-trail inv rtranclp-dpll-bj-atms-in-trail-in-set st **by** auto
moreover have no-dup (trail T)
using n-d inv rtranclp-dpll-bj-no-dup st **by** blast
moreover have inv: inv T
using inv rtranclp-dpll-bj-inv st **by** blast
moreover
have decomp: all-decomposition-implies-m (clauses T) (get-all-marked-decomposition (trail T))
using (inv S) decomp rtranclp-dpll-bj-all-decomposition-implies-inv st **by** blast
ultimately have unsatisfiable (set-mset (clauses T))
 \vee (trail T \models asm clauses T \wedge satisfiable (set-mset (clauses T)))
using (finite A) dpll-backjump-final-state **by** force
then show ?thesis
by (meson (inv S) rtranclp-dpll-bj-sat-iff satisfiable-carac st true-annots-true-cls)
qed

corollary full-dpll-backjump-final-state-from-init-state:
fixes A :: 'v literal multiset set **and** S T :: 'st

```

assumes
  full: full dpll-bj S T and
  trail S = [] and
  clauses S = N and
  inv S
shows unsatisfiable (set-mset N)  $\vee$  (trail T  $\models_{asm}$  N  $\wedge$  satisfiable (set-mset N))
using assms full-dpll-backjump-final-state[of S T set-mset N] by auto

lemma tranclp-dpll-bj-trail-mes-decreasing-prop:
assumes dpll: dpll-bj++ S T and inv: inv S and
  N-A: atms-of-msu (clauses S)  $\subseteq$  atms-of-ms A and
  M-A: atm-of ' lits-of (trail S)  $\subseteq$  atms-of-ms A and
  n-d: no-dup (trail S) and
  fin-A: finite A
shows (2+card (atms-of-ms A))  $\wedge$  (1+card (atms-of-ms A))
  -  $\mu_C$  (1+card (atms-of-ms A)) (2+card (atms-of-ms A)) (trail-weight T)
  < (2+card (atms-of-ms A))  $\wedge$  (1+card (atms-of-ms A))
  -  $\mu_C$  (1+card (atms-of-ms A)) (2+card (atms-of-ms A)) (trail-weight S)
using dpll
proof (induction)
case base
then show ?case
  using N-A M-A n-d dpll-bj-trail-mes-decreasing-prop fin-A inv by blast
next
case (step T U) note st = this(1) and dpll = this(2) and IH = this(3)
have atms-of-msu (clauses S) = atms-of-msu (clauses T)
  using rtranclp-dpll-bj-atms-of-ms-clauses-inv by (metis dpll-bj-clauses dpll-bj-inv inv st
    tranclpD)
then have N-A': atms-of-msu (clauses T)  $\subseteq$  atms-of-ms A
  using N-A by auto
moreover have M-A': atm-of ' lits-of (trail T)  $\subseteq$  atms-of-ms A
  by (meson M-A N-A inv rtranclp-dpll-bj-atms-in-trail-in-set st dpll
    tranclp.r-into-trancl tranclp-into-rtranclp tranclp-trans)
moreover have nd: no-dup (trail T)
  by (metis inv n-d rtranclp-dpll-bj-no-dup st tranclp-into-rtranclp)
moreover have inv T
  by (meson dpll dpll-bj-inv inv rtranclp-dpll-bj-inv st tranclp-into-rtranclp)
ultimately show ?case
  using IH dpll-bj-trail-mes-decreasing-prop[of T U A] dpll fin-A by linarith
qed

end

```

14.4 CDCL

14.4.1 Learn and Forget

```

locale learn-ops =
  dpll-state trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
for
  trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
  clauses :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and tl-trail :: 'st  $\Rightarrow$  'st and
  add-clNOT remove-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st +
fixes
  learn-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool

```

```

begin
inductive learn :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
  clauses S  $\models_{pm}$  C  $\implies$  atms-of C  $\subseteq$  atms-of-msu (clauses S)  $\cup$  atm-of ' (lits-of (trail S))
     $\implies$  learn-cond C S
     $\implies$  T  $\sim$  add-clsNOT C S
     $\implies$  learn S T
inductive-cases learnE: learn S T

lemma learn- $\mu_C$ -stable:
  assumes learn S T and no-dup (trail S)
  shows  $\mu_C$  A B (trail-weight S) =  $\mu_C$  A B (trail-weight T)
  using assms by (auto elim: learnE)
end

locale forget-ops =
  dpll-state trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT
for
  trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
  clauses :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and tl-trail :: 'st  $\Rightarrow$  'st and
  add-clsNOT remove-clsNOT:: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st +
fixes
  forget-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool
begin
inductive forgetNOT :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
  forgetNOT:clauses S - replicate-mset (count (clauses S) C) C  $\models_{pm}$  C
     $\implies$  forget-cond C S
     $\implies$  C  $\in \#$  clauses S
     $\implies$  T  $\sim$  remove-clsNOT C S
     $\implies$  forgetNOT S T
inductive-cases forgetE: forgetNOT S T

lemma forget- $\mu_C$ -stable:
  assumes forgetNOT S T
  shows  $\mu_C$  A B (trail-weight S) =  $\mu_C$  A B (trail-weight T)
  using assms by (auto elim!: forgetE)
end

locale learn-and-forgetNOT =
  learn-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT learn-cond +
  forget-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT forget-cond
for
  trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
  clauses :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clsNOT remove-clsNOT:: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  learn-cond forget-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool
begin
inductive learn-and-forgetNOT :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool
where
  lf-learn: learn S T  $\implies$  learn-and-forgetNOT S T |
  lf-forget: forgetNOT S T  $\implies$  learn-and-forgetNOT S T
end

```

14.4.2 Definition of CDCL

locale *conflict-driven-clause-learning-ops* =
dpll-with-backjumping-ops *trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT}*
propagate-conds inv backjump-conds +
learn-and-forget_{NOT} trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT} learn-cond
forget-cond
for
trail :: 'st \Rightarrow ('v, unit, unit) marked-lits **and**
clauses :: 'st \Rightarrow 'v clauses **and**
prepend-trail :: ('v, unit, unit) marked-lit \Rightarrow 'st \Rightarrow 'st **and**
tl-trail :: 'st \Rightarrow 'st **and**
add-cl_{NOT} remove-cl_{NOT} :: 'v clause \Rightarrow 'st \Rightarrow 'st **and**
propagate-conds :: ('v, unit, unit) marked-lit \Rightarrow 'st \Rightarrow bool **and**
inv :: 'st \Rightarrow bool **and**
backjump-conds :: 'v clause \Rightarrow 'v literal \Rightarrow 'st \Rightarrow 'st \Rightarrow bool **and**
learn-cond forget-cond :: 'v clause \Rightarrow 'st \Rightarrow bool
begin

inductive *cdcl_{NOT}* :: 'st \Rightarrow 'st \Rightarrow bool **for** *S* :: 'st **where**
c-dpll-bj: *dpll-bj* *S S'* \Longrightarrow *cdcl_{NOT}* *S S'* |
c-learn: *learn* *S S'* \Longrightarrow *cdcl_{NOT}* *S S'* |
c-forget_{NOT}: *forget_{NOT}* *S S'* \Longrightarrow *cdcl_{NOT}* *S S'*

lemma *cdcl_{NOT}-all-induct*[*consumes 1, case-names dpll-bj learn forget_{NOT}*]:
fixes *S T* :: 'st
assumes *cdcl_{NOT}* *S T* **and**
dpll: $\bigwedge T. \text{dpll-bj } S T \Longrightarrow P S T$ **and**
learning:
 $\bigwedge C T. \text{clauses } S \models_{pm} C \Longrightarrow$
 $\text{atms-of } C \subseteq \text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of ' (lits-of (trail } S)) \Longrightarrow$
 $T \sim \text{add-cl}_{NOT} C S \Longrightarrow$
 $P S T$ **and**
forgetting: $\bigwedge C T. \text{clauses } S - \text{replicate-mset } (\text{count } (\text{clauses } S) C) C \models_{pm} C \Longrightarrow$
 $C \in \# \text{clauses } S \Longrightarrow$
 $T \sim \text{remove-cl}_{NOT} C S \Longrightarrow$
 $P S T$
shows *P S T*
using *assms(1)* **by** (*induction rule: cdcl_{NOT}.induct*)
(*auto intro: assms(2, 3, 4) elim!: learnE forgetE*)+

lemma *cdcl_{NOT}-no-dup*:
assumes
cdcl_{NOT} *S T* **and**
inv *S* **and**
no-dup (trail *S*)
shows *no-dup* (trail *T*)
using *assms* **by** (*induction rule: cdcl_{NOT}-all-induct*) (*auto intro: dpll-bj-no-dup*)

Consistency of the trail **lemma** *cdcl_{NOT}-consistent*:

assumes
cdcl_{NOT} *S T* **and**
inv *S* **and**
no-dup (trail *S*)
shows *consistent-interp* (lits-of (trail *T*))
using *cdcl_{NOT}-no-dup*[*OF assms*] *distinctconsistent-interp* **by** *fast*

The subtle problem here is that tautologies can be removed, meaning that some variable can disappear of the problem. It is also possible that some variable of the trail are not in the clauses anymore.

lemma *cdcl_{NOT}-atms-of-ms-clauses-decreasing:*

assumes *cdcl_{NOT} S T and inv S and no-dup (trail S)*
shows *atms-of-msu (clauses T) \subseteq atms-of-msu (clauses S) \cup atm-of ‘ (lits-of (trail S))*
using *assms by (induction rule: cdcl_{NOT}-all-induct)*
(auto dest!: dpll-bj-atms-of-ms-clauses-inv set-mp simp add: atms-of-ms-def Union-eq)

lemma *cdcl_{NOT}-atms-in-trail:*

assumes *cdcl_{NOT} S T and inv S and no-dup (trail S)*
and *atm-of ‘ (lits-of (trail S)) \subseteq atms-of-msu (clauses S)*
shows *atm-of ‘ (lits-of (trail T)) \subseteq atms-of-msu (clauses S)*
using *assms by (induction rule: cdcl_{NOT}-all-induct) (auto simp add: dpll-bj-atms-in-trail)*

lemma *cdcl_{NOT}-atms-in-trail-in-set:*

assumes
cdcl_{NOT} S T and inv S and no-dup (trail S) and
atms-of-msu (clauses S) \subseteq A and
atm-of ‘ (lits-of (trail S)) \subseteq A
shows *atm-of ‘ (lits-of (trail T)) \subseteq A*
using *assms*
by *(induction rule: cdcl_{NOT}-all-induct)*
(simp-all add: dpll-bj-atms-in-trail-in-set dpll-bj-atms-of-ms-clauses-inv)

lemma *cdcl_{NOT}-all-decomposition-implies:*

assumes *cdcl_{NOT} S T and inv S and n-d[simp]: no-dup (trail S) and*
all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S))
shows
all-decomposition-implies-m (clauses T) (get-all-marked-decomposition (trail T))

using *assms(1,2,4)*

proof *(induction rule: cdcl_{NOT}-all-induct)*

case *dpll-bj*

then show *?case*

using *dpll-bj-all-decomposition-implies-inv n-d by blast*

next

case *learn*

then show *?case by (auto simp add: all-decomposition-implies-def)*

next

case *(forget_{NOT} C T) note cls-C = this(1) and C = this(2) and T = this(3) and inv = this(4)*

and

decomp = this(5)

show *?case*

unfolding *all-decomposition-implies-def Ball-def*

proof *(intro allI, clarify)*

fix *a b*

assume *(a, b) \in set (get-all-marked-decomposition (trail T))*

then have *($\lambda a. \{\#lit-of\ a\# \}$) ‘ set a \cup set-mset (clauses S) \models_{ps} ($\lambda a. \{\#lit-of\ a\# \}$) ‘ set b*

using *decomp T by (auto simp add: all-decomposition-implies-def)*

moreover

have *C \in set-mset (clauses S)*

by *(simp add: C)*

then have *set-mset (clauses T) \models_{ps} set-mset (clauses S)*

by *(metis (no-types) T clauses-remove-cls_{NOT} cls-C insert-Diff order-refl*

set-mset-minus-replicate-mset(1) state-eq_{NOT}-clauses true-clss-clss-def

```

      true-clss-clss-insert)
    ultimately show  $(\lambda a. \{\#lit\text{-of } a\# \}) \text{ ‘ set } a \cup \text{ set-mset (clauses } T)$ 
       $\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ‘ set } b$ 
      using true-clss-clss-generalise-true-clss-clss by blast
  qed
qed

```

Extension of models lemma $cdcl_{NOT}\text{-bj-sat-ext-iff}$:

```

  assumes  $cdcl_{NOT} S$  T and  $inv S$  and  $n\text{-d: no-dup (trail } S)$ 
  shows  $I \models_{sextm} \text{clauses } S \longleftrightarrow I \models_{sextm} \text{clauses } T$ 
  using assms
proof (induction rule:  $cdcl_{NOT}\text{-all-induct}$ )
  case  $dpll\text{-bj}$ 
  then show ?case by (simp add:  $dpll\text{-bj-clauses}$ )
next
  case (learn C T) note  $T = this(3)$ 
  { fix J
    assume
       $I \models_{sextm} \text{clauses } S$  and
       $I \subseteq J$  and
       $tot$ :  $total\text{-over-}m J (\text{set-mset } (\{\#C\# \} + (\text{clauses } S)))$  and
       $cons$ :  $consistent\text{-interp } J$ 
    then have  $J \models_{sm} \text{clauses } S$  unfolding true-clss-ext-def by auto

    moreover
      with  $\langle \text{clauses } S \models_{pm} C \rangle$  have  $J \models C$ 
      using  $tot cons$  unfolding true-clss-clss-def by auto
    ultimately have  $J \models_{sm} \{\#C\# \} + \text{clauses } S$  by auto
  }
  then have  $H$ :  $I \models_{sextm} (\text{clauses } S) \implies I \models_{sext} \text{insert } C (\text{set-mset } (\text{clauses } S))$ 
  unfolding true-clss-ext-def by auto
  show ?case
  apply standard
  using  $T n\text{-d}$  apply (auto simp add:  $H$ )[]
  using  $T n\text{-d}$  apply simp
  by (metis Diff-insert-absorb insert-subset subsetI subset-antisym
    true-clss-ext-decrease-right-remove-r)
next
  case (forgetNOT C T) note  $cls\text{-}C = this(1)$  and  $T = this(3)$ 
  { fix J
    assume
       $I \models_{sext} \text{set-mset } (\text{clauses } S) - \{C\}$  and
       $I \subseteq J$  and
       $tot$ :  $total\text{-over-}m J (\text{set-mset } (\text{clauses } S))$  and
       $cons$ :  $consistent\text{-interp } J$ 
    then have  $J \models_s \text{set-mset } (\text{clauses } S) - \{C\}$ 
      unfolding true-clss-ext-def by (meson Diff-subset total-over-m-subset)

    moreover
      with  $cls\text{-}C$  have  $J \models C$ 
      using  $tot cons$  unfolding true-clss-clss-def
      by (metis Un-commute forgetNOT.hyps(2) insert-Diff insert-is-Un mem-set-mset-iff order-refl
        set-mset-minus-replicate-mset(1))
    ultimately have  $J \models_{sm} (\text{clauses } S)$  by (metis insert-Diff-single true-clss-insert)
  }

```

then have $H: I \models_{\text{sext}} \text{set-mset} (\text{clauses } S) - \{C\} \implies I \models_{\text{sextm}} (\text{clauses } S)$
 unfolding *true-clss-ext-def* by *blast*
 show ?case using *T* by (auto simp: *true-clss-ext-decrease-right-remove-r H*)
 qed

end — end of *conflict-driven-clause-learning-ops*

14.5 CDCL with invariant

locale *conflict-driven-clause-learning* =
 conflict-driven-clause-learning-ops +
 assumes $\text{cdcl}_{\text{NOT-inv}}: \bigwedge S T. \text{cdcl}_{\text{NOT}} S T \implies \text{inv } S \implies \text{inv } T$
 begin
 sublocale *dpll-with-backjumping*
 apply *unfold-locales*
 using $\text{cdcl}_{\text{NOT}}.\text{simps } \text{cdcl}_{\text{NOT-inv}}$ by *auto*

lemma *rtranclp-cdcl_{NOT-inv}*:
 $\text{cdcl}_{\text{NOT}}^{**} S T \implies \text{inv } S \implies \text{inv } T$
 by (induction rule: *rtranclp-induct*) (auto simp add: $\text{cdcl}_{\text{NOT-inv}}$)

lemma *rtranclp-cdcl_{NOT-no-dup}*:
 assumes $\text{cdcl}_{\text{NOT}}^{**} S T$ and $\text{inv } S$
 and *no-dup* (trail *S*)
 shows *no-dup* (trail *T*)
 using *assms* by (induction rule: *rtranclp-induct*) (auto intro: $\text{cdcl}_{\text{NOT-no-dup}}$ *rtranclp-cdcl_{NOT-inv}*)

lemma *rtranclp-cdcl_{NOT-trail-clauses-bound}*:
 assumes
 $\text{cdcl}: \text{cdcl}_{\text{NOT}}^{**} S T$ and
 $\text{inv}: \text{inv } S$ and
 $\text{n-d}: \text{no-dup} (\text{trail } S)$ and
 $\text{atms-clauses-S}: \text{atms-of-msu} (\text{clauses } S) \subseteq A$ and
 $\text{atms-trail-S}: \text{atm-of } (\text{lits-of } (\text{trail } S)) \subseteq A$
 shows $\text{atm-of } (\text{lits-of } (\text{trail } T)) \subseteq A \wedge \text{atms-of-msu} (\text{clauses } T) \subseteq A$
 using *cdcl*
 proof (induction rule: *rtranclp-induct*)
 case *base*
 then show ?case using $\text{atms-clauses-S } \text{atms-trail-S}$ by *simp*
 next
 case (step *T U*) note $st = \text{this}(1)$ and $\text{cdcl}_{\text{NOT}} = \text{this}(2)$ and $IH = \text{this}(3)$
 have $\text{inv } T$ using $\text{inv } st$ *rtranclp-cdcl_{NOT-inv}* by *blast*
 have *no-dup* (trail *T*)
 using *rtranclp-cdcl_{NOT-no-dup}*[of *S T*] $st \text{cdcl}_{\text{NOT}} \text{inv } \text{n-d}$ by *blast*
 then have $\text{atms-of-msu} (\text{clauses } U) \subseteq A$
 using $\text{cdcl}_{\text{NOT-atms-of-ms-clauses-decreasing}}[\text{OF } \text{cdcl}_{\text{NOT}}] IH \text{n-d } \langle \text{inv } T \rangle$ by *auto*
 moreover
 have $\text{atm-of } (\text{lits-of } (\text{trail } U)) \subseteq A$
 using $\text{cdcl}_{\text{NOT-atms-in-trail-in-set}}[\text{OF } \text{cdcl}_{\text{NOT}}, \text{of } A] \langle \text{no-dup } (\text{trail } T) \rangle$
 by (meson $\text{atms-trail-S } \text{atms-clauses-S } IH \langle \text{inv } T \rangle \text{cdcl}_{\text{NOT}}$)
 ultimately show ?case by *fast*
 qed

lemma *rtranclp-cdcl_{NOT-all-decomposition-implys}*:
 assumes $\text{cdcl}_{\text{NOT}}^{**} S T$ and $\text{inv } S$ and *no-dup* (trail *S*) and
all-decomposition-implys-m (clauses *S*) (*get-all-marked-decomposition* (trail *S*))

shows

all-decomposition-implies-m (*clauses* T) (*get-all-marked-decomposition* (*trail* T))

using *assms* **by** (*induction*)

(*auto intro*: *rtranclp-cdcl_{NOT}-inv cdcl_{NOT}-all-decomposition-implies rtranclp-cdcl_{NOT}-no-dup*)

lemma *rtranclp-cdcl_{NOT}-bj-sat-ext-iff*:

assumes *cdcl_{NOT}** S T and inv S and no-dup* (*trail* S)

shows $I \models_{\text{sextm}} \text{clauses } S \longleftrightarrow I \models_{\text{sextm}} \text{clauses } T$

using *assms* **apply** (*induction rule*: *rtranclp-induct*)

using *cdcl_{NOT}-bj-sat-ext-iff* **by** (*auto intro*: *rtranclp-cdcl_{NOT}-inv rtranclp-cdcl_{NOT}-no-dup*)

definition *cdcl_{NOT}-NOT-all-inv* **where**

$\text{cdcl}_{\text{NOT}}\text{-NOT-all-inv } A \ S \longleftrightarrow (\text{finite } A \wedge \text{inv } S \wedge \text{atms-of-msu } (\text{clauses } S) \subseteq \text{atms-of-ms } A$
 $\wedge \text{atm-of ' lits-of } (\text{trail } S) \subseteq \text{atms-of-ms } A \wedge \text{no-dup } (\text{trail } S))$

lemma *cdcl_{NOT}-NOT-all-inv*:

assumes *cdcl_{NOT}** S T and cdcl_{NOT}-NOT-all-inv A S*

shows *cdcl_{NOT}-NOT-all-inv A T*

using *assms* **unfolding** *cdcl_{NOT}-NOT-all-inv-def*

by (*simp add*: *rtranclp-cdcl_{NOT}-inv rtranclp-cdcl_{NOT}-no-dup rtranclp-cdcl_{NOT}-trail-clauses-bound*)

abbreviation *learn-or-forget* **where**

$\text{learn-or-forget } S \ T \equiv (\lambda S \ T. \text{learn } S \ T \vee \text{forget}_{\text{NOT}} \ S \ T) \ S \ T$

lemma *rtranclp-learn-or-forget-cdcl_{NOT}*:

*learn-or-forget** S T \implies cdcl_{NOT}** S T*

using *rtranclp-mono[of learn-or-forget cdcl_{NOT}] cdcl_{NOT}.c-learn cdcl_{NOT}.c-forget_{NOT}* **by** *blast*

lemma *learn-or-forget-dpll- μ_C* :

assumes

l-f: *learn-or-forget** S T and*

dpll: *dpll-bj T U and*

inv: *cdcl_{NOT}-NOT-all-inv A S*

shows $(2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$

$- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } U)$

$< (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$

$- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } S)$

(*is* $?_{\mu} U < ?_{\mu} S$)

proof –

have $?_{\mu} S = ?_{\mu} T$

using *l-f*

proof (*induction*)

case *base*

then show *?case* **by** *simp*

next

case (*step* $T \ U$)

moreover then have *no-dup* (*trail* T)

using *rtranclp-cdcl_{NOT}-no-dup[of S T] cdcl_{NOT}-NOT-all-inv-def inv*

rtranclp-learn-or-forget-cdcl_{NOT} **by** *auto*

ultimately show *?case*

using *forget- μ_C -stable learn- μ_C -stable inv* **unfolding** *cdcl_{NOT}-NOT-all-inv-def* **by** *presburger*

qed

moreover have *cdcl_{NOT}-NOT-all-inv A T*

using *rtranclp-learn-or-forget-cdcl_{NOT} cdcl_{NOT}-NOT-all-inv l-f inv* **by** *blast*

```

ultimately show ?thesis
  using dpll-bj-trail-mes-decreasing-prop[of T U A, OF dpll] finite
  unfolding cdclNOT-NOT-all-inv-def by linarith
qed

lemma infinite-cdclNOT-exists-learn-and-forget-infinite-chain:
  assumes
     $\bigwedge i. \text{cdcl}_{\text{NOT}} (f\ i) (f(\text{Suc}\ i))$  and
     $\text{inv}: \text{cdcl}_{\text{NOT}}\text{-NOT-all-inv}\ A\ (f\ 0)$ 
  shows  $\exists j. \forall i \geq j. \text{learn-or-forget}\ (f\ i) (f\ (\text{Suc}\ i))$ 
  using assms
proof (induction (2 + card (atms-of-ms A))  $\wedge$  (1 + card (atms-of-ms A))
   $-\mu_C\ (1 + \text{card}\ (\text{atms-of-ms}\ A))\ (2 + \text{card}\ (\text{atms-of-ms}\ A))\ (\text{trail-weight}\ (f\ 0))$ 
  arbitrary: f
  rule: nat-less-induct-case)
case (Suc n) note IH = this(1) and  $\mu = \text{this}(2)$  and  $\text{cdcl}_{\text{NOT}} = \text{this}(3)$  and  $\text{inv} = \text{this}(4)$ 
consider
  ( $\text{dpll-end}$ )  $\exists j. \forall i \geq j. \text{learn-or-forget}\ (f\ i) (f\ (\text{Suc}\ i))$ 
| ( $\text{dpll-more}$ )  $\neg(\exists j. \forall i \geq j. \text{learn-or-forget}\ (f\ i) (f\ (\text{Suc}\ i)))$ 
by blast
then show ?case
proof cases
case dpll-end
  then show ?thesis by auto
next
case dpll-more
  then have  $j: \exists i. \neg \text{learn}\ (f\ i) (f\ (\text{Suc}\ i)) \wedge \neg \text{forget}_{\text{NOT}}\ (f\ i) (f\ (\text{Suc}\ i))$ 
  by blast
  obtain i where
     $\neg \text{learn}\ (f\ i) (f\ (\text{Suc}\ i)) \wedge \neg \text{forget}_{\text{NOT}}\ (f\ i) (f\ (\text{Suc}\ i))$  and
     $\forall k < i. \text{learn-or-forget}\ (f\ k) (f\ (\text{Suc}\ k))$ 
  proof -
    obtain  $i_0$  where  $\neg \text{learn}\ (f\ i_0) (f\ (\text{Suc}\ i_0)) \wedge \neg \text{forget}_{\text{NOT}}\ (f\ i_0) (f\ (\text{Suc}\ i_0))$ 
    using j by auto
    then have  $\{i. i \leq i_0 \wedge \neg \text{learn}\ (f\ i) (f\ (\text{Suc}\ i)) \wedge \neg \text{forget}_{\text{NOT}}\ (f\ i) (f\ (\text{Suc}\ i))\} \neq \{\}$ 
    by auto
    let ?I =  $\{i. i \leq i_0 \wedge \neg \text{learn}\ (f\ i) (f\ (\text{Suc}\ i)) \wedge \neg \text{forget}_{\text{NOT}}\ (f\ i) (f\ (\text{Suc}\ i))\}$ 
    let ?i = Min ?I
    have finite ?I
    by auto
    have  $\neg \text{learn}\ (f\ ?i) (f\ (\text{Suc}\ ?i)) \wedge \neg \text{forget}_{\text{NOT}}\ (f\ ?i) (f\ (\text{Suc}\ ?i))$ 
    using Min-in[OF (finite ?I) (?I  $\neq \{\}$ )] by auto
    moreover have  $\forall k < ?i. \text{learn-or-forget}\ (f\ k) (f\ (\text{Suc}\ k))$ 
    using Min.coboundedI[of  $\{i. i \leq i_0 \wedge \neg \text{learn}\ (f\ i) (f\ (\text{Suc}\ i)) \wedge \neg \text{forget}_{\text{NOT}}\ (f\ i) (f\ (\text{Suc}\ i))\}$ , simplified]
    by (meson  $\neg \text{learn}\ (f\ i_0) (f\ (\text{Suc}\ i_0)) \wedge \neg \text{forget}_{\text{NOT}}\ (f\ i_0) (f\ (\text{Suc}\ i_0))$ ) less-imp-le
    dual-order.trans not-le
    ultimately show ?thesis using that by blast
  qed
qed
def g  $\equiv \lambda n. f\ (n + \text{Suc}\ i)$ 
have dpll-bj (f i) (g 0)
  using  $\neg \text{learn}\ (f\ i) (f\ (\text{Suc}\ i)) \wedge \neg \text{forget}_{\text{NOT}}\ (f\ i) (f\ (\text{Suc}\ i))$  cdclNOT cdclNOT.cases
  g-def by auto
{
  fix j

```

```

assume  $j \leq i$ 
then have  $\text{learn-or-forget}^{**} (f\ 0) (f\ j)$ 
  apply ( $\text{induction } j$ )
  apply  $\text{simp}$ 
  by ( $\text{metis (no-types, lifting) Suc-leD Suc-le-lessD rtranclp.simps}$ 
     $\langle \forall k < i. \text{learn } (f\ k) (f\ (\text{Suc } k)) \vee \text{forget}_{NOT} (f\ k) (f\ (\text{Suc } k)) \rangle$ )
}
then have  $\text{learn-or-forget}^{**} (f\ 0) (f\ i)$  by  $\text{blast}$ 
then have  $(2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$ 
   $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } (g\ 0))$ 
   $< (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$ 
   $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } (f\ 0))$ 
using  $\text{learn-or-forget-dpll-}\mu_C[\text{of } f\ 0\ f\ i\ g\ 0\ A]$   $\text{inv } \langle \text{dpll-bj } (f\ i) (g\ 0) \rangle$ 
unfolding  $\text{cdcl}_{NOT}\text{-NOT-all-inv-def}$  by  $\text{linarith}$ 

moreover have  $\text{cdcl}_{NOT}\text{-i: } \text{cdcl}_{NOT}^{**} (f\ 0) (g\ 0)$ 
  using  $\text{rtranclp-learn-or-forget-cdcl}_{NOT}[\text{of } f\ 0\ f\ i]$   $\langle \text{learn-or-forget}^{**} (f\ 0) (f\ i) \rangle$ 
   $\text{cdcl}_{NOT}[\text{of } i]$  unfolding  $g\text{-def}$  by  $\text{auto}$ 
moreover have  $\bigwedge i. \text{cdcl}_{NOT} (g\ i) (g\ (\text{Suc } i))$ 
  using  $\text{cdcl}_{NOT} g\text{-def}$  by  $\text{auto}$ 
moreover have  $\text{cdcl}_{NOT}\text{-NOT-all-inv } A (g\ 0)$ 
  using  $\text{inv } \text{cdcl}_{NOT}\text{-i } \text{rtranclp-cdcl}_{NOT}\text{-trail-clauses-bound } g\text{-def } \text{cdcl}_{NOT}\text{-NOT-all-inv}$  by  $\text{auto}$ 
ultimately obtain  $j$  where  $j: \bigwedge i. i \geq j \implies \text{learn-or-forget } (g\ i) (g\ (\text{Suc } i))$ 
  using  $IH$  unfolding  $\mu[\text{symmetric}]$  by  $\text{presburger}$ 
show  $?thesis$ 
  proof
    {
      fix  $k$ 
      assume  $k \geq j + \text{Suc } i$ 
      then have  $\text{learn-or-forget } (f\ k) (f\ (\text{Suc } k))$ 
        using  $j[\text{of } k - \text{Suc } i]$  unfolding  $g\text{-def}$  by  $\text{auto}$ 
      }
      then show  $\forall k \geq j + \text{Suc } i. \text{learn-or-forget } (f\ k) (f\ (\text{Suc } k))$ 
        by  $\text{auto}$ 
    }
  qed
qed
next
case  $0$  note  $H = \text{this}(1)$  and  $\text{cdcl}_{NOT} = \text{this}(2)$  and  $\text{inv} = \text{this}(3)$ 
show  $?case$ 
  proof ( $\text{rule ccontr}$ )
    assume  $\neg ?case$ 
    then have  $j: \exists i. \neg \text{learn } (f\ i) (f\ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f\ i) (f\ (\text{Suc } i))$ 
      by  $\text{blast}$ 
    obtain  $i$  where
       $\neg \text{learn } (f\ i) (f\ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f\ i) (f\ (\text{Suc } i))$  and
       $\forall k < i. \text{learn-or-forget } (f\ k) (f\ (\text{Suc } k))$ 
    proof -
      obtain  $i_0$  where  $\neg \text{learn } (f\ i_0) (f\ (\text{Suc } i_0)) \wedge \neg \text{forget}_{NOT} (f\ i_0) (f\ (\text{Suc } i_0))$ 
        using  $j$  by  $\text{auto}$ 
      then have  $\{i. i \leq i_0 \wedge \neg \text{learn } (f\ i) (f\ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f\ i) (f\ (\text{Suc } i))\} \neq \{\}$ 
        by  $\text{auto}$ 
      let  $?I = \{i. i \leq i_0 \wedge \neg \text{learn } (f\ i) (f\ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f\ i) (f\ (\text{Suc } i))\}$ 
      let  $?i = \text{Min } ?I$ 
      have  $\text{finite } ?I$ 
        by  $\text{auto}$ 

```

```

have  $\neg \text{learn } (f \text{ ?}i) (f (\text{Suc } ?i)) \wedge \neg \text{forget}_{NOT} (f \text{ ?}i) (f (\text{Suc } ?i))$ 
  using Min-in[OF (finite ?I) (?! ≠ {})] by auto
moreover have  $\forall k < ?i. \text{learn-or-forget } (f k) (f (\text{Suc } k))$ 
  using Min.coboundedI[of {i. i ≤ i0 ∧ ¬ learn (f i) (f (Suc i)) ∧ ¬ forgetNOT (f i) (f (Suc i))}, simplified]
  by (meson (¬ learn (f i0) (f (Suc i0)) ∧ ¬ forgetNOT (f i0) (f (Suc i0))) less-imp-le
    dual-order.trans not-le)
ultimately show ?thesis using that by blast
qed
have dpll-bj (f i) (f (Suc i))
  using (¬ learn (f i) (f (Suc i)) ∧ ¬ forgetNOT (f i) (f (Suc i))) cdclNOT cdclNOT.cases
  by blast
{
  fix j
  assume  $j \leq i$ 
  then have learn-or-forget** (f 0) (f j)
    apply (induction j)
    apply simp
    by (metis (no-types, lifting) Suc-leD Suc-le-lessD rtranclp.simps
      (∀ k < i. learn (f k) (f (Suc k)) ∨ forgetNOT (f k) (f (Suc k))))
}
then have learn-or-forget** (f 0) (f i) by blast

then show False
  using learn-or-forget-dpll-μC[of f 0 f i f (Suc i) A] inv 0
  (dpll-bj (f i) (f (Suc i))) unfolding cdclNOT-NOT-all-inv-def by linarith
qed
qed

```

lemma *wf-cdcl_{NOT}-no-learn-and-forget-infinite-chain:*

```

assumes
  no-infinite-lf:  $\bigwedge f j. \neg (\forall i \geq j. \text{learn-or-forget } (f i) (f (\text{Suc } i)))$ 
shows wf { $(T, S). \text{cdcl}_{NOT} S T \wedge \text{cdcl}_{NOT}\text{-NOT-all-inv } A S$ } (is wf { $(T, S). \text{cdcl}_{NOT} S T \wedge ?\text{inv } S$ })
  unfolding wf-iff-no-infinite-down-chain
proof (rule ccontr)
  assume  $\neg \neg (\exists f. \forall i. (f (\text{Suc } i), f i) \in \{(T, S). \text{cdcl}_{NOT} S T \wedge ?\text{inv } S\})$ 
  then obtain f where
     $\forall i. \text{cdcl}_{NOT} (f i) (f (\text{Suc } i)) \wedge ?\text{inv } (f i)$ 
  by fast
  then have  $\exists j. \forall i \geq j. \text{learn-or-forget } (f i) (f (\text{Suc } i))$ 
    using infinite-cdclNOT-exists-learn-and-forget-infinite-chain[of f] by meson
  then show False using no-infinite-lf by blast
qed

```

lemma *inv-and-tranclp-cdcl_{NOT}-tranclp-cdcl_{NOT}-and-inv:*

```

 $\text{cdcl}_{NOT}^{++} S T \wedge \text{cdcl}_{NOT}\text{-NOT-all-inv } A S \longleftrightarrow (\lambda S T. \text{cdcl}_{NOT} S T \wedge \text{cdcl}_{NOT}\text{-NOT-all-inv } A S)^{++} S T$ 
  (is  $?A \wedge ?I \longleftrightarrow ?B$ )
proof
  assume  $?A \wedge ?I$ 
  then have  $?A$  and  $?I$  by blast+
  then show  $?B$ 
    apply induction
    apply (simp add: tranclp.r-into-trancl)

```

by (metis (no-types, lifting) cdcl_{NOT}-NOT-all-inv tranclp.simps tranclp-into-rtranclp)
 next
 assume ?B
 then have ?A by induction auto
 moreover have ?I using ⟨?B⟩ tranclpD by fastforce
 ultimately show ?A ∧ ?I by blast
 qed

lemma wf-tranclp-cdcl_{NOT}-no-learn-and-forget-infinite-chain:

assumes
 no-infinite-lf: $\bigwedge f j. \neg (\forall i \geq j. \text{learn-or-forget } (f i) (f (\text{Suc } i)))$
 shows wf $\{(T, S). \text{cdcl}_{NOT}^{++} S T \wedge \text{cdcl}_{NOT}\text{-NOT-all-inv } A S\}$
 using wf-tranclp[OF wf-cdcl_{NOT}-no-learn-and-forget-infinite-chain[OF no-infinite-lf]]
 apply (rule wf-subset)
 by (auto simp: trancl-set-tranclp inv-and-tranclp-cdcl_{NOT}-tranclp-cdcl_{NOT}-and-inv)

lemma cdcl_{NOT}-final-state:

assumes
 n-s: no-step cdcl_{NOT} S and
 inv: cdcl_{NOT}-NOT-all-inv A S and
 decomp: all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S))
 shows unsatisfiable (set-mset (clauses S))
 $\vee (\text{trail } S \models_{asm} \text{clauses } S \wedge \text{satisfiable } (\text{set-mset } (\text{clauses } S)))$

proof —

have n-s': no-step dpll-bj S
 using n-s by (auto simp: cdcl_{NOT}.simps)
 show ?thesis
 apply (rule dpll-backjump-final-state[of S A])
 using inv decomp n-s' unfolding cdcl_{NOT}-NOT-all-inv-def by auto

qed

lemma full-cdcl_{NOT}-final-state:

assumes
 full: full cdcl_{NOT} S T and
 inv: cdcl_{NOT}-NOT-all-inv A S and
 n-d: no-dup (trail S) and
 decomp: all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S))
 shows unsatisfiable (set-mset (clauses T))
 $\vee (\text{trail } T \models_{asm} \text{clauses } T \wedge \text{satisfiable } (\text{set-mset } (\text{clauses } T)))$

proof —

have st: cdcl_{NOT}** S T and n-s: no-step cdcl_{NOT} T
 using full unfolding full-def by blast+
 have n-s': cdcl_{NOT}-NOT-all-inv A T
 using cdcl_{NOT}-NOT-all-inv inv st by blast
 moreover have all-decomposition-implies-m (clauses T) (get-all-marked-decomposition (trail T))
 using cdcl_{NOT}-NOT-all-inv-def decomp inv rtranclp-cdcl_{NOT}-all-decomposition-implies st by auto
 ultimately show ?thesis
 using cdcl_{NOT}-final-state n-s by blast

qed

end — end of conflict-driven-clause-learning

14.6 Termination

14.6.1 Restricting learn and forget

locale *conflict-driven-clause-learning-learning-before-backjump-only-distinct-learnt* =
conflict-driven-clause-learning trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT}
propagate-conds inv backjump-conds
 $\lambda C S. \text{distinct-mset } C \wedge \neg \text{tautology } C \wedge \text{learn-restrictions } C S \wedge$
 $(\exists F K d F' C' L. \text{trail } S = F' @ \text{Marked } K () \# F \wedge C = C' + \{\#L\} \wedge F \models_{as} CNot C'$
 $\wedge C' + \{\#L\} \notin \# \text{ clauses } S)$
 $\lambda C S. \neg(\exists F' F K d L. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{as} CNot (C - \{\#L\}))$
 $\wedge \text{forget-restrictions } C S$
for
trail :: 'st \Rightarrow ('v::linorder, unit, unit) marked-lits **and**
clauses :: 'st \Rightarrow 'v clauses **and**
prepend-trail :: ('v, unit, unit) marked-lit \Rightarrow 'st \Rightarrow 'st **and**
tl-trail :: 'st \Rightarrow 'st **and**
add-cl_{NOT} remove-cl_{NOT} :: 'v clause \Rightarrow 'st \Rightarrow 'st **and**
propagate-conds :: ('v, unit, unit) marked-lit \Rightarrow 'st \Rightarrow bool **and**
inv :: 'st \Rightarrow bool **and**
backjump-conds :: 'v clause \Rightarrow 'v literal \Rightarrow 'st \Rightarrow 'st \Rightarrow bool **and**
learn-restrictions forget-restrictions :: 'v clause \Rightarrow 'st \Rightarrow bool
begin

lemma *cdcl_{NOT}-learn-all-induct*[consumes 1, case-names *dpll-bj learn forget_{NOT}*]:
fixes *S T* :: 'st
assumes *cdcl_{NOT} S T* **and**
dpll: $\bigwedge T. \text{dpll-bj } S T \Longrightarrow P S T$ **and**
learning:
 $\bigwedge C F K F' C' L T. \text{clauses } S \models_{pm} C$
 $\Longrightarrow \text{atms-of } C \subseteq \text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of ' (lits-of (trail } S))$
 $\Longrightarrow \text{distinct-mset } C \Longrightarrow \neg \text{tautology } C \Longrightarrow \text{learn-restrictions } C S$
 $\Longrightarrow \text{trail } S = F' @ \text{Marked } K () \# F \Longrightarrow C = C' + \{\#L\} \Longrightarrow F \models_{as} CNot C'$
 $\Longrightarrow C' + \{\#L\} \notin \# \text{ clauses } S \Longrightarrow T \sim \text{add-cl}_{NOT} C S$
 $\Longrightarrow P S T$ **and**
forgetting: $\bigwedge C T. \text{clauses } S - \text{replicate-mset } (\text{count } (\text{clauses } S) C) C \models_{pm} C$
 $\Longrightarrow C \in \# \text{ clauses } S$
 $\Longrightarrow \neg(\exists F' F K L. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{as} CNot (C - \{\#L\}))$
 $\Longrightarrow T \sim \text{remove-cl}_{NOT} C S$
 $\Longrightarrow \text{forget-restrictions } C S \Longrightarrow P S T$
shows *P S T*
using *assms(1)*
apply (*induction rule*: *cdcl_{NOT}.induct*)
apply (*auto dest*: *assms(2) simp add: learn-ops-axioms*)[]
apply (*auto elim*!: *learn-ops.learn.cases[OF learn-ops-axioms] dest: assms(3)*)[]
apply (*auto elim*!: *forget-ops.forget_{NOT}.cases[OF forget-ops-axioms] dest*!: *assms(4)*)
done

lemma *rtranclp-cdcl_{NOT}-inv*:
 $\text{cdcl}_{NOT}^{**} S T \Longrightarrow \text{inv } S \Longrightarrow \text{inv } T$
apply (*induction rule*: *rtranclp-induct*)
apply *simp*
using *cdcl_{NOT}-inv unfolding conflict-driven-clause-learning-def*
conflict-driven-clause-learning-axioms-def **by** *blast*

lemma *learn-always-simple-clauses*:

assumes
learn: *learn S T* **and**
n-d: *no-dup (trail S)*
shows *set-mset (clauses T - clauses S)*
 \subseteq *build-all-simple-clss (atms-of-msu (clauses S) \cup atm-of ' lits-of (trail S))*

proof

fix *C* **assume** *C*: *C \in set-mset (clauses T - clauses S)*
have *distinct-mset C \neg tautology C* **using** *learn C n-d* **by** (*elim learnE*; *auto*)
then have *C \in build-all-simple-clss (atms-of C)*
using *distinct-mset-not-tautology-implies-in-build-all-simple-clss* **by** *blast*
moreover have *atms-of C \subseteq atms-of-msu (clauses S) \cup atm-of ' lits-of (trail S)*
using *learn C n-d* **by** (*elim learnE*) (*auto simp: atms-of-ms-def atms-of-def image-Un true-annots-CNot-all-atms-defined*)
moreover have *finite (atms-of-msu (clauses S) \cup atm-of ' lits-of (trail S))*
by *auto*
ultimately show *C \in build-all-simple-clss (atms-of-msu (clauses S) \cup atm-of ' lits-of (trail S))*
using *build-all-simple-clss-mono* **by** (*metis (no-types) insert-subset mk-disjoint-insert*)

qed

definition *conflicting-bj-clss S \equiv*
 $\{C + \{\#L\# \} \mid C \text{ L. } C + \{\#L\# \} \in \# \text{ clauses } S \wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$
 $\wedge (\exists F' K F. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{as} CNot C)\}$

lemma *conflicting-bj-clss-remove-clcls_{NOT}[simp]*:
 $\text{conflicting-bj-clss } (\text{remove-clcls}_{NOT} C S) = \text{conflicting-bj-clss } S - \{C\}$
unfolding *conflicting-bj-clss-def* **by** *fastforce*

lemma *conflicting-bj-clss-add-clcls_{NOT}-state-eq*:
 $T \sim \text{add-clcls}_{NOT} C' S \implies \text{no-dup } (\text{trail } S) \implies \text{conflicting-bj-clss } T$
 $= \text{conflicting-bj-clss } S$
 $\cup (\text{if } \exists C L. C' = C + \{\#L\# \} \wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$
 $\wedge (\exists F' K d F. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{as} CNot C)$
 $\text{then } \{C'\} \text{ else } \{\})$
unfolding *conflicting-bj-clss-def* **by** *auto metis+*

lemma *conflicting-bj-clss-add-clcls_{NOT}*:
 $\text{no-dup } (\text{trail } S) \implies$
 $\text{conflicting-bj-clss } (\text{add-clcls}_{NOT} C' S)$
 $= \text{conflicting-bj-clss } S$
 $\cup (\text{if } \exists C L. C' = C + \{\#L\# \} \wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$
 $\wedge (\exists F' K d F. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{as} CNot C)$
 $\text{then } \{C'\} \text{ else } \{\})$
using *conflicting-bj-clss-add-clcls_{NOT}-state-eq* **by** *auto*

lemma *conflicting-bj-clss-incl-clauses*:
 $\text{conflicting-bj-clss } S \subseteq \text{set-mset } (\text{clauses } S)$
unfolding *conflicting-bj-clss-def* **by** *auto*

lemma *finite-conflicting-bj-clss[simp]*:
 $\text{finite } (\text{conflicting-bj-clss } S)$
using *conflicting-bj-clss-incl-clauses[of S]* *rev-finite-subset* **by** *blast*

lemma *learn-conflicting-increasing*:
 $\text{no-dup } (\text{trail } S) \implies \text{learn } S T \implies \text{conflicting-bj-clss } S \subseteq \text{conflicting-bj-clss } T$
apply (*elim learnE*)

by (subst conflicting-bj-clss-add-cl_{NOT}-state-eq[of T]) auto

abbreviation conflicting-bj-clss-yet b S \equiv
 $3 \wedge b - \text{card} (\text{conflicting-bj-clss } S)$

abbreviation $\mu_L :: \text{nat} \Rightarrow 'st \Rightarrow \text{nat} \times \text{nat}$ **where**
 $\mu_L b S \equiv (\text{conflicting-bj-clss-yet } b S, \text{card} (\text{set-mset} (\text{clauses } S)))$

lemma do-not-forget-before-backtrack-rule-clause-learned-clause-untouched:

assumes forget_{NOT} S T

shows conflicting-bj-clss S = conflicting-bj-clss T

using assms **apply** induction

unfolding conflicting-bj-clss-def

by (metis (no-types, lifting) Diff-insert-absorb Set.set-insert clauses-remove-cl_{NOT}
diff-union-cancelR insert-iff mem-set-mset-iff order-refl set-mset-minus-replicate-mset(1)
state-eq_{NOT}-clauses state-eq_{NOT}-trail trail-remove-cl_{NOT})

lemma forget- μ_L -decrease:

assumes forget_{NOT}: forget_{NOT} S T

shows $(\mu_L b T, \mu_L b S) \in \text{less-than} <*\text{lex}*> \text{less-than}$

proof –

have card (set-mset (clauses T)) < card (set-mset (clauses S))

using forget_{NOT} **apply** induction

by (metis card-Diff1-less clauses-remove-cl_{NOT} finite-set-mset mem-set-mset-iff order-refl
set-mset-minus-replicate-mset(1) state-eq_{NOT}-clauses)

then show ?thesis

unfolding do-not-forget-before-backtrack-rule-clause-learned-clause-untouched[OF forget_{NOT}]

by auto

qed

lemma set-condition-or-split:

$\{a. (a = b \vee Q a) \wedge S a\} = (\text{if } S b \text{ then } \{b\} \text{ else } \{\}) \cup \{a. Q a \wedge S a\}$

by auto

lemma set-insert-neq:

$A \neq \text{insert } a A \longleftrightarrow a \notin A$

by auto

lemma learn- μ_L -decrease:

assumes learnST: learn S T **and** n-d: no-dup (trail S) **and**

A: atms-of-msu (clauses S) \cup atm-of ' lits-of (trail S) \subseteq A **and**

fin-A: finite A

shows $(\mu_L (\text{card } A) T, \mu_L (\text{card } A) S) \in \text{less-than} <*\text{lex}*> \text{less-than}$

proof –

have [simp]: (atms-of-msu (clauses T) \cup atm-of ' lits-of (trail T))

= (atms-of-msu (clauses S) \cup atm-of ' lits-of (trail S))

using learnST n-d **by** (elim learnE) auto

then have card (atms-of-msu (clauses T) \cup atm-of ' lits-of (trail T))

= card (atms-of-msu (clauses S) \cup atm-of ' lits-of (trail S))

by (auto intro!: card-mono)

then have $3: (3::\text{nat}) \wedge \text{card} (\text{atms-of-msu} (\text{clauses } T) \cup \text{atm-of ' lits-of} (\text{trail } T))$

= $3 \wedge \text{card} (\text{atms-of-msu} (\text{clauses } S) \cup \text{atm-of ' lits-of} (\text{trail } S))$

by (auto intro: power-mono)

moreover have conflicting-bj-clss S \subseteq conflicting-bj-clss T

```

    using learnST n-d by (simp add: learn-conflicting-increasing)
  moreover have conflicting-bj-clss S ≠ conflicting-bj-clss T
  using learnST
  proof (elim learnE, goal-cases)
    case (1 C) note clss-S = this(1) and atms-C = this(2) and inv = this(3) and T = this(4)
    then obtain F K F' C' L where
      tr-S: trail S = F' @ Marked K () # F and
      C: C = C' + {#L#} and
      F: F ⊨as CNot C' and
      C-S: C' + {#L#} ∉# clauses S
    by blast
    moreover have distinct-mset C ⊢ tautology C using inv by blast+
    ultimately have C' + {#L#} ∈ conflicting-bj-clss T
      using T n-d unfolding conflicting-bj-clss-def by fastforce
    moreover have C' + {#L#} ∉ conflicting-bj-clss S
      using C-S unfolding conflicting-bj-clss-def by auto
    ultimately show ?case by blast
  qed
  moreover have fin-T: finite (conflicting-bj-clss T)
    using learnST by induction (auto simp add: conflicting-bj-clss-add-clssNOT)
  ultimately have card (conflicting-bj-clss T) ≥ card (conflicting-bj-clss S)
    using card-mono by blast

  moreover
  have fin': finite (atms-of-msu (clauses T) ∪ atm-of ' lits-of (trail T))
    by auto
  have 1: atms-of-ms (conflicting-bj-clss T) ⊆ atms-of-msu (clauses T)
    unfolding conflicting-bj-clss-def atms-of-ms-def by auto
  have 2:  $\bigwedge x. x \in \text{conflicting-bj-clss } T \implies \neg \text{tautology } x \wedge \text{distinct-mset } x$ 
    unfolding conflicting-bj-clss-def by auto
  have T: conflicting-bj-clss T
    ⊆ build-all-simple-clss (atms-of-msu (clauses T) ∪ atm-of ' lits-of (trail T))
    by standard (meson 1 2 fin' ⟨finite (conflicting-bj-clss T)⟩ build-all-simple-clss-mono
      distinct-mset-set-def simplified-in-build-all subsetCE sup.coboundedI1)
  moreover
  then have #:  $3 \wedge \text{card (atms-of-msu (clauses T) \cup atm-of ' lits-of (trail T))}$ 
    ≥ card (conflicting-bj-clss T)
    by (meson Nat.le-trans build-all-simple-clss-card build-all-simple-clss-finite card-mono fin')
  have atms-of-msu (clauses T) ∪ atm-of ' lits-of (trail T) ⊆ A
    using learnE[OF learnST] A by simp
  then have  $3 \wedge (\text{card } A) \geq \text{card (conflicting-bj-clss T)}$ 
    using # fin-A by (meson build-all-simple-clss-card build-all-simple-clss-finite
      build-all-simple-clss-mono calculation(2) card-mono dual-order.trans)
  ultimately show ?thesis
    using psubset-card-mono[OF fin-T]
    unfolding less-than-iff lex-prod-def by clarify
    (meson ⟨conflicting-bj-clss S ≠ conflicting-bj-clss T⟩
      ⟨conflicting-bj-clss S ⊆ conflicting-bj-clss T⟩
      diff-less-mono2 le-less-trans not-le psubsetI)
  qed

```

We have to assume the following:

- *inv* S: the invariant holds in the initial state.
- A is a (finite *finite* A) superset of the literals in the trail *atm-of ' lits-of (trail S)* ⊆

$atms-of-ms A$ and in the clauses $atms-of-msu (clauses S) \subseteq atms-of-ms A$. This can be the set of all the literals in the starting set of clauses.

- *no-dup* ($trail S$): no duplicate in the trail. This is invariant along the path.

definition μ_{CDCL} **where**

$\mu_{CDCL} A T \equiv ((2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))$
 $- \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight T),$
 $conflicting-bj-clss-yet (card (atms-of-ms A)) T, card (set-mset (clauses T)))$

lemma $cdcl_{NOT}$ -decreasing-measure:

assumes

$cdcl_{NOT} S T$ **and**

$inv: inv S$ **and**

$atm-clss: atms-of-msu (clauses S) \subseteq atms-of-ms A$ **and**

$atm-lits: atm-of ' lits-of (trail S) \subseteq atms-of-ms A$ **and**

$n-d: no-dup (trail S)$ **and**

$fin-A: finite A$

shows $(\mu_{CDCL} A T, \mu_{CDCL} A S)$

$\in less-than <*lex*> (less-than <*lex*> less-than)$

using $assms(1)$

proof *induction*

case $(c-dpll-bj T)$

from $dpll-bj-trail-mes-decreasing-prop[OF this(1) inv atm-clss atm-lits n-d fin-A]$

show $?case$ **unfolding** μ_{CDCL} -def

by $(meson in-lex-prod less-than-iff)$

next

case $(c-learn T)$ **note** $learn = this(1)$

then have $S: trail S = trail T$

using $inv atm-clss atm-lits n-d fin-A$

by $(elim learnE) auto$

show $?case$

using $learn-\mu_L$ -decrease $[OF learn -] atm-clss atm-lits fin-A n-d$ **unfolding** $S \mu_{CDCL}$ -def **by** $auto$

next

case $(c-forget_{NOT} T)$ **note** $forget_{NOT} = this(1)$

have $trail S = trail T$ **using** $forget_{NOT}$ **by** $induction auto$

then show $?case$

using $forget-\mu_L$ -decrease $[OF forget_{NOT}]$ **unfolding** μ_{CDCL} -def **by** $auto$

qed

lemma $wf-cdcl_{NOT}$ -restricted-learning:

assumes $finite A$

shows $wf \{(T, S).$

$(atms-of-msu (clauses S) \subseteq atms-of-ms A \wedge atm-of ' lits-of (trail S) \subseteq atms-of-ms A$

$\wedge no-dup (trail S)$

$\wedge inv S)$

$\wedge cdcl_{NOT} S T \}$

by $(rule wf-wf-if-measure'[of less-than <*lex*> (less-than <*lex*> less-than)])$

$(auto intro: cdcl_{NOT}$ -decreasing-measure $[OF - - - - assms])$

definition $\mu_C' :: 'v literal multiset set \Rightarrow 'st \Rightarrow nat$ **where**

$\mu_C' A T \equiv \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight T)$

definition $\mu_{CDCL}' :: 'v literal multiset set \Rightarrow 'st \Rightarrow nat$ **where**

$\mu_{CDCL}' A T \equiv$

$((2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A)) - \mu_C' A T) * (1 + 3^{card (atms-of-ms A)}) *$

2

+ *conflicting-bj-clss-yet* (*card* (*atms-of-ms A*)) *T* * 2
+ *card* (*set-mset* (*clauses T*))

lemma *cdcl_{NOT}-decreasing-measure'*:

assumes

cdcl_{NOT} S T **and**

inv: inv S **and**

atms-clss: atms-of-msu (*clauses S*) \subseteq *atms-of-ms A* **and**

atms-trail: atm-of ' *lits-of* (*trail S*) \subseteq *atms-of-ms A* **and**

n-d: no-dup (*trail S*) **and**

fin-A: finite A

shows $\mu_{CDCL}' A T < \mu_{CDCL}' A S$

using *assms(1)*

proof (*induction rule: cdcl_{NOT}-learn-all-induct*)

case (*dpll-bj T*)

then have $(2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A T$

$< (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A S$

using *dpll-bj-trail-mes-decreasing-prop fin-A inv n-d atms-clss atms-trail*

unfolding μ_C' -def **by** *blast*

then have *XX*: $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A T) + 1$

$\leq (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A S$

by *auto*

from *mult-le-mono1[OF this, of (1 + 3 \wedge card (atms-of-ms A))]*

have $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A T) *$

$(1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) + (1 + 3 \wedge \text{card } (\text{atms-of-ms } A))$

$\leq ((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A S)$

$* (1 + 3 \wedge \text{card } (\text{atms-of-ms } A))$

unfolding *Nat.add-mult-distrib*

by *presburger*

moreover

have *cl-T-S: clauses T = clauses S*

using *dpll-bj.hyps inv dpll-bj-clauses* **by** *auto*

have *conflicting-bj-clss-yet* (*card* (*atms-of-ms A*)) *S* $< 1 + 3 \wedge \text{card } (\text{atms-of-ms } A)$

by *simp*

ultimately have $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A T)$

$* (1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) + \text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) T$

$< ((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A S) * (1 + 3 \wedge \text{card } (\text{atms-of-ms } A))$

by *linarith*

then have $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A T)$

$* (1 + 3 \wedge \text{card } (\text{atms-of-ms } A))$

$+ \text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) T$

$< ((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A S)$

$* (1 + 3 \wedge \text{card } (\text{atms-of-ms } A))$

$+ \text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) S$

by *linarith*

then have $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A T)$

$* (1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) * 2$

$+ \text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) T * 2$

$< ((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A S)$

$* (1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) * 2$

$+ \text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) S * 2$

by *linarith*

then show ?case **unfolding** μ_{CDCL}' -def *cl-T-S* **by** *presburger*

next

case (*learn* C F' K F C' L T) **note** $\text{clss-}S\text{-}C = \text{this}(1)$ **and** $\text{atms-}C = \text{this}(2)$ **and** $\text{dist} = \text{this}(3)$
and $\text{tauto} = \text{this}(4)$ **and** $\text{learn-restr} = \text{this}(5)$ **and** $\text{tr-}S = \text{this}(6)$ **and** $C' = \text{this}(7)$ **and**
 $F\text{-}C = \text{this}(8)$ **and** $C\text{-new} = \text{this}(9)$ **and** $T = \text{this}(10)$
have $\text{insert } C \text{ (conflicting-bj-clss } S) \subseteq \text{build-all-simple-clss (atms-of-ms } A)$
proof –
have $C \in \text{build-all-simple-clss (atms-of-ms } A)$
by (*metis* (*no-types*, *hide-lams*) *Un-subset-iff atms-of-ms-finite build-all-simple-clss-mono*
contra-subsetD dist distinct-mset-not-tautology-implies-in-build-all-simple-clss
dual-order.trans fin-A atms-C atms-clss atms-trail tauto)
moreover have $\text{conflicting-bj-clss } S \subseteq \text{build-all-simple-clss (atms-of-ms } A)$
unfolding *conflicting-bj-clss-def*
proof
fix $x :: 'v \text{ literal multiset}$
assume $x \in \{C + \{\#L\# \} \mid C \text{ L. } C + \{\#L\# \} \in \# \text{ clauses } S$
 $\wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$
 $\wedge (\exists F' K F. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{\text{as}} C \text{Not } C)$
then have $\exists m \text{ l. } x = m + \{\#l\# \} \wedge m + \{\#l\# \} \in \# \text{ clauses } S$
 $\wedge \text{distinct-mset } (m + \{\#l\# \}) \wedge \neg \text{tautology } (m + \{\#l\# \})$
 $\wedge (\exists ms \text{ l msa. trail } S = ms @ \text{Marked } l () \# msa \wedge msa \models_{\text{as}} C \text{Not } m)$
by *blast*
then show $x \in \text{build-all-simple-clss (atms-of-ms } A)$
by (*meson* *atms-clss atms-of-atms-of-ms-mono atms-of-ms-finite build-all-simple-clss-mono*
distinct-mset-not-tautology-implies-in-build-all-simple-clss fin-A finite-subset
mem-set-mset-iff set-rev-mp)
qed
ultimately show *?thesis*
by *auto*
qed
then have $\text{card (insert } C \text{ (conflicting-bj-clss } S)) \leq 3 \wedge (\text{card (atms-of-ms } A))$
by (*meson* *Nat.le-trans atms-of-ms-finite build-all-simple-clss-card build-all-simple-clss-finite*
card-mono fin-A)
moreover have [*simp*]: $\text{card (insert } C \text{ (conflicting-bj-clss } S))$
 $= \text{Suc (card ((conflicting-bj-clss } S))$
by (*metis* (*no-types*) *C' C-new card-insert-if conflicting-bj-clss-incl-clauses contra-subsetD*
finite-conflicting-bj-clss mem-set-mset-iff)
moreover have [*simp*]: $\text{conflicting-bj-clss (add-cl}_{\text{NOT}} C S) = \text{conflicting-bj-clss } S \cup \{C\}$
using *dist tauto F-C n-d* **by** (*subst conflicting-bj-clss-add-cl}_{\text{NOT}}*)
(force simp add: ac-simps C' tr-S)+
ultimately have [*simp*]: $\text{conflicting-bj-clss-yet (card (atms-of-ms } A)) S$
 $= \text{Suc (conflicting-bj-clss-yet (card (atms-of-ms } A)) (add-cl}_{\text{NOT}} C S))$
by *simp*
have 1: $\text{clauses } T = \text{clauses (add-cl}_{\text{NOT}} C S)$ **using** *T* **by** *auto*
have 2: $\text{conflicting-bj-clss-yet (card (atms-of-ms } A)) T$
 $= \text{conflicting-bj-clss-yet (card (atms-of-ms } A)) (add-cl}_{\text{NOT}} C S)$
using *T* **unfolding** *conflicting-bj-clss-def* **by** *auto*
have 3: $\mu_{C'} A T = \mu_{C'} A (add-cl}_{\text{NOT}} C S)$
using *T* **unfolding** $\mu_{C'}\text{-def}$ **by** *auto*
have $((2 + \text{card (atms-of-ms } A)) \wedge (1 + \text{card (atms-of-ms } A)) - \mu_{C'} A (add-cl}_{\text{NOT}} C S))$
 $* (1 + 3 \wedge \text{card (atms-of-ms } A)) * 2$
 $= ((2 + \text{card (atms-of-ms } A)) \wedge (1 + \text{card (atms-of-ms } A)) - \mu_{C'} A S)$
 $* (1 + 3 \wedge \text{card (atms-of-ms } A)) * 2$
using *n-d* **unfolding** $\mu_{C'}\text{-def}$ **by** *auto*
moreover
have $\text{conflicting-bj-clss-yet (card (atms-of-ms } A)) (add-cl}_{\text{NOT}} C S)$
 $* 2$

```

+ card (set-mset (clauses (add-clNOT C S)))
< conflicting-bj-clss-yet (card (atms-of-ms A)) S * 2
+ card (set-mset (clauses S))
by (simp add: C' C-new n-d)
ultimately show ?case unfolding  $\mu_{CDCL}'$ -def 1 2 3 by presburger
next
case (forgetNOT C T) note T = this(4)
have [simp]:  $\mu_C' A$  (remove-clNOT C S) =  $\mu_C' A S$ 
  unfolding  $\mu_C'$ -def by auto
have forgetNOT S T
  apply (rule forgetNOT.intros) using forgetNOT by auto
then have conflicting-bj-clss T = conflicting-bj-clss S
  using do-not-forget-before-backtrack-rule-clause-learned-clause-untouched by blast
moreover have card (set-mset (clauses T)) < card (set-mset (clauses S))
  by (metis T card-Diff1-less clauses-remove-clNOT finite-set-mset forgetNOT.hyps(2)
    mem-set-mset-iff order-refl set-mset-minus-replicate-mset(1) state-eqNOT-clauses)
ultimately show ?case unfolding  $\mu_{CDCL}'$ -def
  by (metis (no-types) T  $\mu_C' A$  (remove-clNOT C S) =  $\mu_C' A S$ ) add-le-cancel-left
     $\mu_C'$ -def not-le state-eqNOT-trail)
qed

lemma cdclNOT-clauses-bound:
  assumes
    cdclNOT S T and
    inv S and
    atms-of-msu (clauses S)  $\subseteq$  A and
    atm-of '(lits-of (trail S))  $\subseteq$  A and
    n-d: no-dup (trail S) and
    fin-A[simp]: finite A
  shows set-mset (clauses T)  $\subseteq$  set-mset (clauses S)  $\cup$  build-all-simple-clss A
  using assms
proof (induction rule: cdclNOT-learn-all-induct)
  case dpll-bj
  then show ?case using dpll-bj-clauses by simp
next
  case forgetNOT
  then show ?case using clauses-remove-clNOT unfolding state-eqNOT-def by auto
next
  case (learn C F K d F' C' L) note atms-C = this(2) and dist = this(3) and tauto = this(4) and
    T = this(10) and atms-clss-S = this(12) and atms-trail-S = this(13)
  have atms-of C  $\subseteq$  A
    using atms-C atms-clss-S atms-trail-S by auto
  then have build-all-simple-clss (atms-of C)  $\subseteq$  build-all-simple-clss A
    by (simp add: build-all-simple-clss-mono)
  then have C  $\in$  build-all-simple-clss A
    using finite dist tauto
    by (auto dest: distinct-mset-not-tautology-implies-in-build-all-simple-clss)
  then show ?case using T n-d by auto
qed

lemma rtrancpl-cdclNOT-clauses-bound:
  assumes
    cdclNOT** S T and
    inv S and
    atms-of-msu (clauses S)  $\subseteq$  A and

```


$atm\text{-}of \text{ '}(lits\text{-}of \text{ (trail } S)) \subseteq A$ and
 $n\text{-}d: no\text{-}dup \text{ (trail } S)$ and
 $finite: finite \ A$
shows $set\text{-}mset \text{ (clauses } T) \subseteq set\text{-}mset \text{ (clauses } S) \cup build\text{-}all\text{-}simple\text{-}clss \ A$
using $assms(1-5)$
proof *induction*
case *base*
then show *?case* **by** *simp*
next
case $(step \ T \ U)$ **note** $st = this(1)$ and $cdcl_{NOT} = this(2)$ and $IH = this(3)[OF \ this(4-7)]$ and
 $inv = this(4)$ and $atms\text{-}clss\text{-}S = this(5)$ and $atms\text{-}trail\text{-}S = this(6)$ and $finite\text{-}cls\text{-}S = this(7)$
have $inv \ T$
using $rtranclp\text{-}cdcl_{NOT}\text{-}inv \ st \ inv$ **by** *blast*
moreover have $atms\text{-}of\text{-}msu \text{ (clauses } T) \subseteq A$ and $atm\text{-}of \text{ ' } lits\text{-}of \text{ (trail } T) \subseteq A$
using $rtranclp\text{-}cdcl_{NOT}\text{-}trail\text{-}clauses\text{-}bound[OF \ st] \ inv \ atms\text{-}clss\text{-}S \ atms\text{-}trail\text{-}S \ n\text{-}d$ **by** *blast+*
moreover have $no\text{-}dup \text{ (trail } T)$
using $rtranclp\text{-}cdcl_{NOT}\text{-}no\text{-}dup[OF \ st \ \langle inv \ S \rangle \ n\text{-}d]$ **by** *simp*
ultimately have $set\text{-}mset \text{ (clauses } U) \subseteq set\text{-}mset \text{ (clauses } T) \cup build\text{-}all\text{-}simple\text{-}clss \ A$
using $cdcl_{NOT} \ finite \ n\text{-}d$ **by** $(auto \ simp: \ cdcl_{NOT}\text{-}clauses\text{-}bound)$
then show *?case* **using** *IH* **by** *auto*
qed

lemma $rtranclp\text{-}cdcl_{NOT}\text{-}card\text{-}clauses\text{-}bound$:

assumes
 $cdcl_{NOT}^{**} \ S \ T$ and
 $inv \ S$ and
 $atms\text{-}of\text{-}msu \text{ (clauses } S) \subseteq A$ and
 $atm\text{-}of \text{ '}(lits\text{-}of \text{ (trail } S)) \subseteq A$ and
 $n\text{-}d: no\text{-}dup \text{ (trail } S)$ and
 $finite: finite \ A$
shows $card \ (set\text{-}mset \text{ (clauses } T)) \leq card \ (set\text{-}mset \text{ (clauses } S)) + 3 \wedge (card \ A)$
using $rtranclp\text{-}cdcl_{NOT}\text{-}clauses\text{-}bound[OF \ assms] \ finite$ **by** $(meson \ Nat.le\text{-}trans$
 $build\text{-}all\text{-}simple\text{-}clss\text{-}card \ build\text{-}all\text{-}simple\text{-}clss\text{-}finite \ card\text{-}Un\text{-}le \ card\text{-}mono \ finite\text{-}UnI$
 $finite\text{-}set\text{-}mset \ nat\text{-}add\text{-}left\text{-}cancel\text{-}le)$

lemma $rtranclp\text{-}cdcl_{NOT}\text{-}card\text{-}clauses\text{-}bound'$:

assumes
 $cdcl_{NOT}^{**} \ S \ T$ and
 $inv \ S$ and
 $atms\text{-}of\text{-}msu \text{ (clauses } S) \subseteq A$ and
 $atm\text{-}of \text{ '}(lits\text{-}of \text{ (trail } S)) \subseteq A$ and
 $n\text{-}d: no\text{-}dup \text{ (trail } S)$ and
 $finite: finite \ A$
shows $card \ \{C \mid C. C \in \# \text{ clauses } T \wedge (tautology \ C \vee \neg distinct\text{-}mset \ C)\}$
 $\leq card \ \{C \mid C. C \in \# \text{ clauses } S \wedge (tautology \ C \vee \neg distinct\text{-}mset \ C)\} + 3 \wedge (card \ A)$
 $(is \ card \ ?T \leq card \ ?S + -)$

using $rtranclp\text{-}cdcl_{NOT}\text{-}clauses\text{-}bound[OF \ assms] \ finite$

proof –

have $?T \subseteq ?S \cup build\text{-}all\text{-}simple\text{-}clss \ A$
using $rtranclp\text{-}cdcl_{NOT}\text{-}clauses\text{-}bound[OF \ assms]$ **by** *force*
then have $card \ ?T \leq card \ (?S \cup build\text{-}all\text{-}simple\text{-}clss \ A)$
using *finite* **by** $(simp \ add: \ assms(5) \ build\text{-}all\text{-}simple\text{-}clss\text{-}finite \ card\text{-}mono)$
then show *?thesis*
by $(meson \ le\text{-}trans \ build\text{-}all\text{-}simple\text{-}clss\text{-}card \ card\text{-}Un\text{-}le \ local.finite \ nat\text{-}add\text{-}left\text{-}cancel\text{-}le)$

qed

lemma *rtrancpl-cdcl_{NOT}-card-simple-clauses-bound*:

assumes

*cdcl_{NOT}** S T and*

inv S and

atms-of-msu (clauses S) \subseteq A and

atm-of '(lits-of (trail S)) \subseteq A and

n-d: no-dup (trail S) and

finite: finite A

shows *card (set-mset (clauses T))*

\leq card {C. C \in # clauses S \wedge (tautology C \vee \neg distinct-mset C)} + 3 \wedge (card A)

(is card ?T \leq card ?S + -)

using *rtrancpl-cdcl_{NOT}-clauses-bound[OF assms] finite*

proof –

have $\bigwedge x. x \in \# \text{ clauses } T \implies \neg \text{tautology } x \implies \text{distinct-mset } x \implies x \in \text{build-all-simple-clss } A$

using *rtrancpl-cdcl_{NOT}-clauses-bound[OF assms] by (metis (no-types, hide-lams) Un-iff assms(3)*

atms-of-atms-of-ms-mono build-all-simple-clss-mono contra-subsetD

distinct-mset-not-tautology-implies-in-build-all-simple-clss local.finite mem-set-mset-iff

subset-trans)

then have *set-mset (clauses T) \subseteq ?S \cup build-all-simple-clss A*

using *rtrancpl-cdcl_{NOT}-clauses-bound[OF assms] by auto*

then have *card(set-mset (clauses T)) \leq card (?S \cup build-all-simple-clss A)*

using *finite by (simp add: assms(5) build-all-simple-clss-finite card-mono)*

then show *?thesis*

by *(meson le-trans build-all-simple-clss-card card-Un-le local.finite nat-add-left-cancel-le)*

qed

definition *μ_{CDCL}' -bound :: 'v literal multiset set \Rightarrow 'st \Rightarrow nat where*

μ_{CDCL}' -bound A S =

*((2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))) * (1 + 3 \wedge card (atms-of-ms A)) * 2*

*+ 2*3 \wedge (card (atms-of-ms A))*

+ card {C. C \in # clauses S \wedge (tautology C \vee \neg distinct-mset C)} + 3 \wedge (card (atms-of-ms A))

lemma *μ_{CDCL}' -bound-reduce-trail-to_{NOT}[simp]:*

μ_{CDCL}' -bound A (reduce-trail-to_{NOT} M S) = μ_{CDCL}' -bound A S

unfolding *μ_{CDCL}' -bound-def by auto*

lemma *rtrancpl-cdcl_{NOT}- μ_{CDCL}' -bound-reduce-trail-to_{NOT}:*

assumes

*cdcl_{NOT}** S T and*

inv S and

atms-of-msu (clauses S) \subseteq atms-of-ms A and

atm-of '(lits-of (trail S)) \subseteq atms-of-ms A and

n-d: no-dup (trail S) and

finite: finite (atms-of-ms A) and

U: U \sim reduce-trail-to_{NOT} M T

shows *$\mu_{CDCL}' A U \leq \mu_{CDCL}'$ -bound A S*

proof –

have *((2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A)) – $\mu_C' A U$)*

\leq (2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))

by *auto*

then have *((2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A)) – $\mu_C' A U$)*

** (1 + 3 \wedge card (atms-of-ms A)) * 2*

*\leq (2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A)) * (1 + 3 \wedge card (atms-of-ms A)) * 2*

using *mult-le-mono1* by *blast*
 moreover
 have *conflicting-bj-clss-yet* (*card* (*atms-of-ms* *A*)) $T * 2 \leq 2 * 3 \wedge \text{card} \text{ (atms-of-ms } A)$
 by *linarith*
 moreover have *card* (*set-mset* (*clauses* *U*))
 $\leq \text{card} \{C. C \in \# \text{ clauses } S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\} + 3 \wedge \text{card} \text{ (atms-of-ms } A)$
 using *rtranclp-cdcl_{NOT}-card-simple-clauses-bound*[*OF assms(1-6)*] *U* by *auto*
 ultimately show *?thesis*
 unfolding $\mu_{CDCL}'\text{-def}$ $\mu_{CDCL}'\text{-bound-def}$ by *linarith*
 qed

lemma *rtranclp-cdcl_{NOT}- μ_{CDCL}' -bound*:

assumes
 $cdcl_{NOT}^{**} S T$ and
inv *S* and
 $\text{atms-of-msu} \text{ (clauses } S) \subseteq \text{atms-of-ms } A$ and
 $\text{atm-of } '(\text{lits-of } (\text{trail } S)) \subseteq \text{atms-of-ms } A$ and
n-d: *no-dup* (*trail* *S*) and
finite: *finite* (*atms-of-ms* *A*)
 shows $\mu_{CDCL}' A T \leq \mu_{CDCL}'\text{-bound } A S$
 proof –
 have $\mu_{CDCL}' A (\text{reduce-trail-to}_{NOT} (\text{trail } T) T) = \mu_{CDCL}' A T$
 unfolding $\mu_{CDCL}'\text{-def}$ $\mu_C'\text{-def}$ *conflicting-bj-clss-def* by *auto*
 then show *?thesis* using *rtranclp-cdcl_{NOT}- μ_{CDCL}' -bound-reduce-trail-to_{NOT}*[*OF assms, of - trail T*]
state-eq_{NOT}-ref by *fastforce*
 qed

lemma *rtranclp- μ_{CDCL}' -bound-decreasing*:

assumes
 $cdcl_{NOT}^{**} S T$ and
inv *S* and
 $\text{atms-of-msu} \text{ (clauses } S) \subseteq \text{atms-of-ms } A$ and
 $\text{atm-of } '(\text{lits-of } (\text{trail } S)) \subseteq \text{atms-of-ms } A$ and
n-d: *no-dup* (*trail* *S*) and
finite[simp]: *finite* (*atms-of-ms* *A*)
 shows $\mu_{CDCL}'\text{-bound } A T \leq \mu_{CDCL}'\text{-bound } A S$
 proof –
 have $\{C. C \in \# \text{ clauses } T \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\}$
 $\subseteq \{C. C \in \# \text{ clauses } S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\}$ (is $?T \subseteq ?S$)
 proof (rule *Set.subsetI*)
 fix *C* assume $C \in ?T$
 then have *C-T*: $C \in \# \text{ clauses } T$ and *t-d*: $\text{tautology } C \vee \neg \text{distinct-mset } C$
 by *auto*
 then have $C \notin \text{build-all-simple-clss} \text{ (atms-of-ms } A)$
 by (*auto dest: build-all-simple-clssE*)
 then show $C \in ?S$
 using *C-T* *rtranclp-cdcl_{NOT}-clauses-bound*[*OF assms*] *t-d* by *force*
 qed
 then have $\text{card} \{C. C \in \# \text{ clauses } T \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\} \leq$
 $\text{card} \{C. C \in \# \text{ clauses } S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\}$
 by (*simp add: card-mono*)
 then show *?thesis*
 unfolding $\mu_{CDCL}'\text{-bound-def}$ by *auto*
 qed

end — end of *conflict-driven-clause-learning-learning-before-backjump-only-distinct-learnt*

14.7 CDCL with restarts

14.7.1 Definition

```

locale restart-ops =
  fixes
     $cdcl_{NOT} :: 'st \Rightarrow 'st \Rightarrow bool$  and
     $restart :: 'st \Rightarrow 'st \Rightarrow bool$ 
  begin
  inductive  $cdcl_{NOT}\text{-raw-restart} :: 'st \Rightarrow 'st \Rightarrow bool$  where
     $cdcl_{NOT} S T \Longrightarrow cdcl_{NOT}\text{-raw-restart} S T \mid$ 
     $restart S T \Longrightarrow cdcl_{NOT}\text{-raw-restart} S T$ 

  end

locale conflict-driven-clause-learning-with-restarts =
  conflict-driven-clause-learning trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
  propagate-conds inv backjump-conds learn-cond forget-cond
  for
     $trail :: 'st \Rightarrow ('v, unit, unit) \text{ marked-lits}$  and
     $clauses :: 'st \Rightarrow 'v \text{ clauses}$  and
     $prepend-trail :: ('v, unit, unit) \text{ marked-lit} \Rightarrow 'st \Rightarrow 'st$  and
     $tl-trail :: 'st \Rightarrow 'st$  and
     $add-cl_{NOT} \text{ remove-cl}_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$  and
     $propagate-conds :: ('v, unit, unit) \text{ marked-lit} \Rightarrow 'st \Rightarrow bool$  and
     $inv :: 'st \Rightarrow bool$  and
     $backjump-conds :: 'v \text{ clause} \Rightarrow 'v \text{ literal} \Rightarrow 'st \Rightarrow 'st \Rightarrow bool$  and
     $learn-cond \text{ forget-cond} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow bool$ 
  begin

  lemma  $cdcl_{NOT}\text{-iff-}cdcl_{NOT}\text{-raw-restart-no-restarts}$ :
     $cdcl_{NOT} S T \longleftrightarrow restart\text{-ops}.cdcl_{NOT}\text{-raw-restart} cdcl_{NOT} (\lambda\text{-}. False) S T$ 
    (is  $?C S T \longleftrightarrow ?R S T$ )
  proof
    fix  $S T$ 
    assume  $?C S T$ 
    then show  $?R S T$  by (simp add: restart-ops.cdclNOT-raw-restart.intros(1))
  next
    fix  $S T$ 
    assume  $?R S T$ 
    then show  $?C S T$ 
    apply (cases rule: restart-ops.cdclNOT-raw-restart.cases)
    using ( $?R S T$ ) by fast+
  qed

  lemma  $cdcl_{NOT}\text{-}cdcl_{NOT}\text{-raw-restart}$ :
     $cdcl_{NOT} S T \Longrightarrow restart\text{-ops}.cdcl_{NOT}\text{-raw-restart} cdcl_{NOT} restart S T$ 
    by (simp add: restart-ops.cdclNOT-raw-restart.intros(1))
  end

```

14.7.2 Increasing restarts

To add restarts we need some assumptions on the predicate (called $cdcl_{NOT}$ here):

- a function f that is strictly monotonic. The first step is actually only used as a restart to clean the state (e.g. to ensure that the trail is empty). Then we assume that $(1::'a) \leq f$ n for $(1::'a) \leq n$: it means that between two consecutive restarts, at least one step will be done. This is necessary to avoid sequence. like: full – restart – full – ...
- a measure μ : it should decrease under the assumptions $bound_inv$, whenever a $cdcl_{NOT}$ or a $restart$ is done. A parameter is given to μ : for conflict- driven clause learning, it is an upper-bound of the clauses. We are assuming that such a bound can be found after a restart whenever the invariant holds.
- we also assume that the measure decrease after any $cdcl_{NOT}$ step.
- an invariant on the states $cdcl_{NOT}\text{-inv}$ that also holds after restarts.
- it is *not required* that the measure decrease with respect to restarts, but the measure has to be bound by some function $\mu\text{-bound}$ taking the same parameter as μ and the initial state of the considered $cdcl_{NOT}$ chain.

```

locale  $cdcl_{NOT}\text{-increasing-restarts-ops} =$ 
   $restart\text{-ops}$   $cdcl_{NOT}$   $restart$  for
     $restart :: 'st \Rightarrow 'st \Rightarrow bool$  and
     $cdcl_{NOT} :: 'st \Rightarrow 'st \Rightarrow bool +$ 
fixes
   $f :: nat \Rightarrow nat$  and
   $bound\_inv :: 'bound \Rightarrow 'st \Rightarrow bool$  and
   $\mu :: 'bound \Rightarrow 'st \Rightarrow nat$  and
   $cdcl_{NOT}\text{-inv} :: 'st \Rightarrow bool$  and
   $\mu\text{-bound} :: 'bound \Rightarrow 'st \Rightarrow nat$ 
assumes
   $f$ :  $unbounded\ f$  and
   $f\text{-ge-1}$ :  $\bigwedge n. n \geq 1 \implies f\ n \neq 0$  and
   $bound\_inv$ :  $\bigwedge A\ S\ T. cdcl_{NOT}\text{-inv}\ S \implies bound\_inv\ A\ S \implies cdcl_{NOT}\ S\ T \implies bound\_inv\ A\ T$  and
   $cdcl_{NOT}\text{-measure}$ :  $\bigwedge A\ S\ T. cdcl_{NOT}\text{-inv}\ S \implies bound\_inv\ A\ S \implies cdcl_{NOT}\ S\ T \implies \mu\ A\ T < \mu$ 
 $A\ S$  and
   $measure\_bound2$ :  $\bigwedge A\ T\ U. cdcl_{NOT}\text{-inv}\ T \implies bound\_inv\ A\ T \implies cdcl_{NOT}^{**}\ T\ U$ 
     $\implies \mu\ A\ U \leq \mu\text{-bound}\ A\ T$  and
   $measure\_bound4$ :  $\bigwedge A\ T\ U. cdcl_{NOT}\text{-inv}\ T \implies bound\_inv\ A\ T \implies cdcl_{NOT}^{**}\ T\ U$ 
     $\implies \mu\text{-bound}\ A\ U \leq \mu\text{-bound}\ A\ T$  and
   $cdcl_{NOT}\text{-restart-inv}$ :  $\bigwedge A\ U\ V. cdcl_{NOT}\text{-inv}\ U \implies restart\ U\ V \implies bound\_inv\ A\ U \implies bound\_inv$ 
 $A\ V$ 
and
   $exists\_bound$ :  $\bigwedge R\ S. cdcl_{NOT}\text{-inv}\ R \implies restart\ R\ S \implies \exists A. bound\_inv\ A\ S$  and
   $cdcl_{NOT}\text{-inv}$ :  $\bigwedge S\ T. cdcl_{NOT}\text{-inv}\ S \implies cdcl_{NOT}\ S\ T \implies cdcl_{NOT}\text{-inv}\ T$  and
   $cdcl_{NOT}\text{-inv-restart}$ :  $\bigwedge S\ T. cdcl_{NOT}\text{-inv}\ S \implies restart\ S\ T \implies cdcl_{NOT}\text{-inv}\ T$ 
begin

lemma  $cdcl_{NOT}\text{-}cdcl_{NOT}\text{-inv}$ :
  assumes
     $(cdcl_{NOT} \text{~} n)$   $S\ T$  and
     $cdcl_{NOT}\text{-inv}\ S$ 
  shows  $cdcl_{NOT}\text{-inv}\ T$ 
  using  $assms$  by ( $induction\ n\ arbitrary:\ T$ ) ( $auto\ intro: bound\_inv\ cdcl_{NOT}\text{-inv}$ )

lemma  $cdcl_{NOT}\text{-bound-inv}$ :
  assumes

```

$(cdcl_{NOT} \rightsquigarrow n) S T$ **and**
 $cdcl_{NOT-inv} S$
 $bound-inv A S$
shows $bound-inv A T$
using *assms* **by** (*induction* n *arbitrary*: T) (*auto* *intro*: $bound-inv\ cdcl_{NOT} - cdcl_{NOT-inv}$)

lemma *rtrancplp-cdcl_{NOT}-cdcl_{NOT-inv}*:
assumes
 $cdcl_{NOT}^{**} S T$ **and**
 $cdcl_{NOT-inv} S$
shows $cdcl_{NOT-inv} T$
using *assms* **by** *induction* (*auto* *intro*: $cdcl_{NOT-inv}$)

lemma *rtrancplp-cdcl_{NOT}-bound-inv*:
assumes
 $cdcl_{NOT}^{**} S T$ **and**
 $bound-inv A S$ **and**
 $cdcl_{NOT-inv} S$
shows $bound-inv A T$
using *assms* **by** *induction* (*auto* *intro*: $bound-inv\ rtrancplp-cdcl_{NOT} - cdcl_{NOT-inv}$)

lemma *cdcl_{NOT}-comp-n-le*:
assumes
 $(cdcl_{NOT} \rightsquigarrow (Suc\ n)) S T$ **and**
 $bound-inv A S$
 $cdcl_{NOT-inv} S$
shows $\mu A\ T < \mu A\ S - n$
using *assms*
proof (*induction* n *arbitrary*: T)
case 0
then show *?case* **using** $cdcl_{NOT-measure}$ **by** *auto*
next
case $(Suc\ n)$ **note** $IH = this(1)[OF - this(3)\ this(4)]$ **and** $S-T = this(2)$ **and** $b-inv = this(3)$ **and**
 $c-inv = this(4)$
obtain $U :: 'st$ **where** $S-U: (cdcl_{NOT} \rightsquigarrow (Suc\ n)) S U$ **and** $U-T: cdcl_{NOT}\ U\ T$ **using** $S-T$ **by** *auto*
then have $\mu A\ U < \mu A\ S - n$ **using** $IH[of\ U]$ **by** *simp*
moreover
have $bound-inv A U$
using $S-U\ b-inv\ cdcl_{NOT-bound-inv}\ c-inv$ **by** *blast*
then have $\mu A\ T < \mu A\ U$ **using** $cdcl_{NOT-measure}[OF - -\ U-T]\ S-U\ c-inv\ cdcl_{NOT} - cdcl_{NOT-inv}$
by *auto*
ultimately show *?case* **by** *linarith*
qed

lemma *wf-cdcl_{NOT}*:
 $wf\ \{(T, S). cdcl_{NOT}\ S\ T \wedge cdcl_{NOT-inv}\ S \wedge bound-inv\ A\ S\}$ (**is** $wf\ ?A$)
apply (*rule* $wfP-if-measure2[of\ -\ -\ \mu\ A]$)
using $cdcl_{NOT-comp-n-le}[of\ 0\ -\ A]$ **by** *auto*

lemma *rtrancplp-cdcl_{NOT}-measure*:
assumes
 $cdcl_{NOT}^{**} S T$ **and**
 $bound-inv A S$ **and**
 $cdcl_{NOT-inv} S$
shows $\mu A\ T \leq \mu A\ S$

```

using assms
proof (induction rule: rtrancpl-induct)
  case base
  then show ?case by auto
next
  case (step T U) note IH = this(3)[OF this(4) this(5)] and st = this(1) and cdclNOT = this(2) and
    b-inv = this(4) and c-inv = this(5)
  have bound-inv A T
    by (meson cdclNOT-bound-inv rtrancpl-imp-relpowp st step.prems)
  moreover have cdclNOT-inv T
    using c-inv rtrancpl-cdclNOT-cdclNOT-inv st by blast
  ultimately have  $\mu A U < \mu A T$  using cdclNOT-measure[OF - - cdclNOT] by auto
  then show ?case using IH by linarith
qed

```

lemma *cdcl_{NOT}-comp-bounded*:

```

assumes
  bound-inv A S and cdclNOT-inv S and  $m \geq 1 + \mu A S$ 
shows  $\neg(\text{cdcl}_{NOT} \rightsquigarrow^m) S T$ 
using assms cdclNOT-comp-n-le[of m-1 S T A] by fastforce

```

- $f n < m$ ensures that at least one step has been done.

inductive *cdcl_{NOT}-restart* **where**

```

restart-step: ( $\text{cdcl}_{NOT} \rightsquigarrow^m$ ) S T  $\implies m \geq f n \implies \text{restart } T U$ 
   $\implies \text{cdcl}_{NOT}\text{-restart } (S, n) (U, \text{Suc } n) \mid$ 
restart-full: full1 cdclNOT S T  $\implies \text{cdcl}_{NOT}\text{-restart } (S, n) (T, \text{Suc } n)$ 

```

lemmas *cdcl_{NOT}-with-restart-induct* = *cdcl_{NOT}-restart.induct[split-format(complete),*
OF cdcl_{NOT}-increasing-restarts-ops-axioms]

lemma *cdcl_{NOT}-restart-cdcl_{NOT}-raw-restart*:

```

cdclNOT-restart S T  $\implies \text{cdcl}_{NOT}\text{-raw-restart}^{**} (fst S) (fst T)$ 

```

proof (*induction rule: cdcl_{NOT}-restart.induct*)

case (*restart-step* *m S T n U*)

then have *cdcl_{NOT}** S T* **by** (*meson relpowp-imp-rtrancpl*)

then have *cdcl_{NOT}-raw-restart** S T* **using** *cdcl_{NOT}-raw-restart.intros(1)*
rtrancpl-mono[of cdcl_{NOT} cdcl_{NOT}-raw-restart] **by** *blast*

moreover have *cdcl_{NOT}-raw-restart T U*

using $\langle \text{restart } T U \rangle$ *cdcl_{NOT}-raw-restart.intros(2)* **by** *blast*

ultimately show ?*case* **by** *auto*

next

case (*restart-full* *S T*)

then have *cdcl_{NOT}** S T* **unfolding** *full1-def* **by** *auto*

then show ?*case* **using** *cdcl_{NOT}-raw-restart.intros(1)*
rtrancpl-mono[of cdcl_{NOT} cdcl_{NOT}-raw-restart] **by** *auto*

qed

lemma *cdcl_{NOT}-with-restart-bound-inv*:

assumes

cdcl_{NOT}-restart S T **and**

bound-inv A (fst S) **and**

cdcl_{NOT}-inv (fst S)

shows *bound-inv A (fst T)*

using *assms apply (induction rule: cdcl_{NOT}-restart.induct)*

prefer 2 apply (*metis rtrancpl-unfold fstI full1-def rtrancpl-cdcl_{NOT}-bound-inv*)
by (*metis cdcl_{NOT}-bound-inv cdcl_{NOT}-cdcl_{NOT}-inv cdcl_{NOT}-restart-inv fst-conv*)

lemma *cdcl_{NOT}-with-restart-cdcl_{NOT}-inv*:

assumes
cdcl_{NOT}-restart S T and
cdcl_{NOT}-inv (fst S)
shows *cdcl_{NOT}-inv (fst T)*
using *assms apply induction*
apply (*metis cdcl_{NOT}-cdcl_{NOT}-inv cdcl_{NOT}-inv-restart fst-conv*)
apply (*metis fstI full-def full-unfold rtrancpl-cdcl_{NOT}-cdcl_{NOT}-inv*)
done

lemma *rtrancpl-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv*:

assumes
*cdcl_{NOT}-restart** S T and*
cdcl_{NOT}-inv (fst S)
shows *cdcl_{NOT}-inv (fst T)*
using *assms by induction (auto intro: cdcl_{NOT}-with-restart-cdcl_{NOT}-inv)*

lemma *rtrancpl-cdcl_{NOT}-with-restart-bound-inv*:

assumes
*cdcl_{NOT}-restart** S T and*
cdcl_{NOT}-inv (fst S) and
bound-inv A (fst S)
shows *bound-inv A (fst T)*
using *assms apply induction*
apply (*simp add: cdcl_{NOT}-cdcl_{NOT}-inv cdcl_{NOT}-with-restart-bound-inv*)
using *cdcl_{NOT}-with-restart-bound-inv rtrancpl-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv by blast*

lemma *cdcl_{NOT}-with-restart-increasing-number*:

cdcl_{NOT}-restart S T \implies snd T = 1 + snd S
by (*induction rule: cdcl_{NOT}-restart.induct*) *auto*
end

locale *cdcl_{NOT}-increasing-restarts =*

cdcl_{NOT}-increasing-restarts-ops restart cdcl_{NOT} f bound-inv μ cdcl_{NOT}-inv μ -bound
for

trail :: 'st \Rightarrow ('v, unit, unit) marked-lits and
clauses :: 'st \Rightarrow 'v clauses and
prepend-trail :: ('v, unit, unit) marked-lit \Rightarrow 'st \Rightarrow 'st and
tl-trail :: 'st \Rightarrow 'st and
add-cls_{NOT} remove-cls_{NOT}:: 'v clause \Rightarrow 'st \Rightarrow 'st and
f :: nat \Rightarrow nat and
restart :: 'st \Rightarrow 'st \Rightarrow bool and
bound-inv :: 'bound \Rightarrow 'st \Rightarrow bool and
 μ :: 'bound \Rightarrow 'st \Rightarrow nat and
cdcl_{NOT} :: 'st \Rightarrow 'st \Rightarrow bool and
cdcl_{NOT}-inv :: 'st \Rightarrow bool and
 μ -bound :: 'bound \Rightarrow 'st \Rightarrow nat +

assumes

measure-bound: $\bigwedge A T V n. cdcl_{NOT}\text{-inv } T \implies bound\text{-inv } A T$
 $\implies cdcl_{NOT}\text{-restart } (T, n) (V, Suc\ n) \implies \mu\ A\ V \leq \mu\text{-bound } A\ T$ **and**
cdcl_{NOT}-raw-restart- μ -bound:
cdcl_{NOT}-restart (T, a) (V, b) $\implies cdcl_{NOT}\text{-inv } T \implies bound\text{-inv } A\ T$

$\implies \mu\text{-bound } A \ V \leq \mu\text{-bound } A \ T$
begin

lemma *rtrancpl-cdcl_{NOT}-raw-restart- μ -bound:*
 $\text{cdcl}_{NOT}\text{-restart}^{**} (T, a) (V, b) \implies \text{cdcl}_{NOT}\text{-inv } T \implies \text{bound-inv } A \ T$
 $\implies \mu\text{-bound } A \ V \leq \mu\text{-bound } A \ T$
apply (*induction rule: rtrancpl-induct2*)
apply *simp*
by (*metis cdcl_{NOT}-raw-restart- μ -bound dual-order.trans fst-conv*
rtrancpl-cdcl_{NOT}-with-restart-bound-inv rtrancpl-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv)

lemma *cdcl_{NOT}-raw-restart-measure-bound:*
 $\text{cdcl}_{NOT}\text{-restart} (T, a) (V, b) \implies \text{cdcl}_{NOT}\text{-inv } T \implies \text{bound-inv } A \ T$
 $\implies \mu \ A \ V \leq \mu\text{-bound } A \ T$
apply (*cases rule: cdcl_{NOT}-restart.cases*)
apply *simp*
using *measure-bound relpowp-imp-rtrancpl* **apply** *fastforce*
by (*metis full-def full-unfold measure-bound2 prod.inject*)

lemma *rtrancpl-cdcl_{NOT}-raw-restart-measure-bound:*
 $\text{cdcl}_{NOT}\text{-restart}^{**} (T, a) (V, b) \implies \text{cdcl}_{NOT}\text{-inv } T \implies \text{bound-inv } A \ T$
 $\implies \mu \ A \ V \leq \mu\text{-bound } A \ T$
apply (*induction rule: rtrancpl-induct2*)
apply (*simp add: measure-bound2*)
by (*metis dual-order.trans fst-conv measure-bound2 r-into-rtrancpl rtrancpl.rtrancpl-refl*
rtrancpl-cdcl_{NOT}-with-restart-bound-inv rtrancpl-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv
rtrancpl-cdcl_{NOT}-raw-restart- μ -bound)

lemma *wf-cdcl_{NOT}-restart:*
 $\text{wf } \{(T, S). \text{cdcl}_{NOT}\text{-restart } S \ T \wedge \text{cdcl}_{NOT}\text{-inv } (\text{fst } S)\}$ (**is** *wf ?A*)
proof (*rule ccontr*)
assume $\neg ?thesis$
then obtain *g* **where**
 $g: \bigwedge i. \text{cdcl}_{NOT}\text{-restart } (g \ i) \ (g \ (\text{Suc } i))$ **and**
 $\text{cdcl}_{NOT}\text{-inv-}g: \bigwedge i. \text{cdcl}_{NOT}\text{-inv } (\text{fst } (g \ i))$
unfolding *wf-iff-no-infinite-down-chain* **by** *fast*

have *snd-g*: $\bigwedge i. \text{snd } (g \ i) = i + \text{snd } (g \ 0)$
apply (*induct-tac i*)
apply *simp*
by (*metis Suc-eq-plus1-left add.commute add.left-commute*
cdcl_{NOT}-with-restart-increasing-number g)
then have *snd-g-0*: $\bigwedge i. i > 0 \implies \text{snd } (g \ i) = i + \text{snd } (g \ 0)$
by *blast*
have *unbounded-f-g*: $\text{unbounded } (\lambda i. f \ (\text{snd } (g \ i)))$
using *f* **unfolding** *bounded-def* **by** (*metis add.commute f less-or-eq-imp-le snd-g*
not-bounded-nat-exists-larger not-le ordered-cancel-comm-monoid-diff-class.le-iff-add)

{ fix *i*
have *H*: $\bigwedge T \ \text{Ta} \ m. (\text{cdcl}_{NOT} \ \widetilde{\sim} \ m) \ T \ \text{Ta} \implies \text{no-step } \text{cdcl}_{NOT} \ T \implies m = 0$
apply (*case-tac m*) **apply** *simp* **by** (*meson relpowp-E2*)
have $\exists \ T \ m. (\text{cdcl}_{NOT} \ \widetilde{\sim} \ m) \ (\text{fst } (g \ i)) \ T \wedge m \geq f \ (\text{snd } (g \ i))$
using *g[of i]* **apply** (*cases rule: cdcl_{NOT}-restart.cases*)
apply *auto*
using *g[of Suc i]* *f-ge-1* **apply** (*cases rule: cdcl_{NOT}-restart.cases*)

```

    apply (auto simp add: full1-def full-def dest: H dest: tranclpD)
    using H Suc-leI leD by blast
  } note H = this
obtain A where bound-inv A (fst (g 1))
  using g[of 0] cdclNOT-inv-g[of 0] apply (cases rule: cdclNOT-restart.cases)
  apply (metis One-nat-def cdclNOT-inv exists-bound fst-conv relpowp-imp-rtranclp
    rtranclp-induct)
  using H[of 1] unfolding full1-def by (metis One-nat-def Suc-eq-plus1 diff-is-0-eq' diff-zero
    f-ge-1 fst-conv le-add2 relpowp-E2 snd-conv)
let ?j =  $\mu$ -bound A (fst (g 1)) + 1
obtain j where
  j: f (snd (g j)) > ?j and j > 1
  using unbounded-f-g not-bounded-nat-exists-larger by blast
{
  fix i j
  have cdclNOT-with-restart:  $j \geq i \implies \text{cdcl}_{\text{NOT}}\text{-restart}^{**} (g i) (g j)$ 
    apply (induction j)
    apply simp
    by (metis g le-Suc-eq rtranclp.rtrancl-into-rtrancl rtranclp.rtrancl-refl)
  } note cdclNOT-restart = this
have cdclNOT-inv (fst (g (Suc 0)))
  by (simp add: cdclNOT-inv-g)
have cdclNOT-restart** (fst (g 1), snd (g 1)) (fst (g j), snd (g j))
  using <j > 1> by (simp add: cdclNOT-restart)
have  $\mu$  A (fst (g j))  $\leq$   $\mu$ -bound A (fst (g 1))
  apply (rule rtranclp-cdclNOT-raw-restart-measure-bound)
  using <cdclNOT-restart** (fst (g 1), snd (g 1)) (fst (g j), snd (g j))> apply blast
  apply (simp add: cdclNOT-inv-g)
  using <bound-inv A (fst (g 1))> apply simp
done
then have  $\mu$  A (fst (g j))  $\leq$  ?j
  by auto
have inv: bound-inv A (fst (g j))
  using <bound-inv A (fst (g 1))> <cdclNOT-inv (fst (g (Suc 0)))>
  <cdclNOT-restart** (fst (g 1), snd (g 1)) (fst (g j), snd (g j))>
  rtranclp-cdclNOT-with-restart-bound-inv by auto
obtain T m where
  cdclNOT-m: (cdclNOT  $\rightsquigarrow$  m) (fst (g j)) T and
  f-m: f (snd (g j))  $\leq$  m
  using H[of j] by blast
have ?j < m
  using f-m j Nat.le-trans by linarith

then show False
  using < $\mu$  A (fst (g j))  $\leq$   $\mu$ -bound A (fst (g 1))>
  cdclNOT-comp-bounded[OF inv cdclNOT-inv-g, of ] cdclNOT-inv-g cdclNOT-m
  <?j < m> by auto
qed

```

lemma *cdcl_{NOT}-restart-steps-bigger-than-bound:*
assumes
 cdcl_{NOT}-restart S T **and**
 bound-inv A (fst S) **and**
 cdcl_{NOT}-inv (fst S) **and**
 f (snd S) > μ -bound A (fst S)

shows $\text{full1 } \text{cdcl}_{NOT} \text{ (fst } S \text{) (fst } T \text{)}$
using assms
proof ($\text{induction rule: } \text{cdcl}_{NOT}\text{-restart.induct}$)
case restart-full
then show $?case$ **by** auto
next
case ($\text{restart-step } m \ S \ T \ n \ U$) **note** $st = \text{this}(1)$ **and** $f = \text{this}(2)$ **and** $\text{bound-inv} = \text{this}(4)$ **and**
 $\text{cdcl}_{NOT}\text{-inv} = \text{this}(5)$ **and** $\mu = \text{this}(6)$
then obtain m' **where** $m: m = \text{Suc } m'$ **by** ($\text{cases } m$) auto
have $\mu \ A \ S - m' = 0$
using $f \ \text{bound-inv} \ \text{cdcl}_{NOT}\text{-inv} \ \mu \ m \ \text{rtrancpl-cdcl}_{NOT}\text{-raw-restart-measure-bound}$ **by** fastforce
then have False **using** $\text{cdcl}_{NOT}\text{-comp-n-le[of } m' \ S \ T \ A \text{]}$ restart-step **unfolding** m **by** simp
then show $?case$ **by** fast
qed

lemma $\text{rtrancpl-cdcl}_{NOT}\text{-with-inv-inv-rtrancpl-cdcl}_{NOT}$:
assumes
 $\text{inv: } \text{cdcl}_{NOT}\text{-inv } S$ **and**
 $\text{binv: } \text{bound-inv } A \ S$
shows $(\lambda S \ T. \text{cdcl}_{NOT} \ S \ T \wedge \text{cdcl}_{NOT}\text{-inv } S \wedge \text{bound-inv } A \ S)^{**} \ S \ T \longleftrightarrow \text{cdcl}_{NOT}^{**} \ S \ T$
(is $?A^{**} \ S \ T \longleftrightarrow ?B^{**} \ S \ T$ **)**
apply ($\text{rule } \text{iffI}$)
using $\text{rtrancpl-mono[of } ?A \ ?B \text{]}$ **apply** blast
apply ($\text{induction rule: } \text{rtrancpl-induct}$)
using $\text{inv } \text{binv}$ **apply** simp
by ($\text{metis (mono-tags, lifting) binv inv rtrancpl.simps rtrancpl-cdcl}_{NOT}\text{-bound-inv}$
 $\text{rtrancpl-cdcl}_{NOT}\text{-cdcl}_{NOT}\text{-inv}$)

lemma $\text{no-step-cdcl}_{NOT}\text{-restart-no-step-cdcl}_{NOT}$:
assumes
 $n\text{-s: no-step } \text{cdcl}_{NOT}\text{-restart } S$ **and**
 $\text{inv: } \text{cdcl}_{NOT}\text{-inv (fst } S \text{)}$ **and**
 $\text{binv: } \text{bound-inv } A \text{ (fst } S \text{)}$
shows $\text{no-step } \text{cdcl}_{NOT} \text{ (fst } S \text{)}$
proof ($\text{rule } \text{ccontr}$)
assume $\neg ?thesis$
then obtain T **where** $T: \text{cdcl}_{NOT} \text{ (fst } S \text{)}$ T
by blast
then obtain U **where** $U: \text{full } (\lambda S \ T. \text{cdcl}_{NOT} \ S \ T \wedge \text{cdcl}_{NOT}\text{-inv } S \wedge \text{bound-inv } A \ S) \ T \ U$
using $\text{wf-exists-normal-form-full[OF wf-cdcl}_{NOT}, \text{ of } A \ T]$ **by** auto
moreover have $\text{inv-T: } \text{cdcl}_{NOT}\text{-inv } T$
using $\langle \text{cdcl}_{NOT} \text{ (fst } S \text{)} \ T \rangle \text{cdcl}_{NOT}\text{-inv inv}$ **by** blast
moreover have $\text{b-inv-T: } \text{bound-inv } A \ T$
using $\langle \text{cdcl}_{NOT} \text{ (fst } S \text{)} \ T \rangle \text{binv bound-inv inv}$ **by** blast
ultimately have $\text{full } \text{cdcl}_{NOT} \ T \ U$
using $\text{rtrancpl-cdcl}_{NOT}\text{-with-inv-inv-rtrancpl-cdcl}_{NOT} \ \text{rtrancpl-cdcl}_{NOT}\text{-bound-inv}$
 $\text{rtrancpl-cdcl}_{NOT}\text{-cdcl}_{NOT}\text{-inv}$ **unfolding** full-def **by** blast
then have $\text{full1 } \text{cdcl}_{NOT} \text{ (fst } S \text{)} \ U$
using $T \ \text{full-fullI}$ **by** metis
then show False **by** ($\text{metis } n\text{-s } \text{prod.collapse restart-full}$)
qed

end

14.8 Merging backjump and learning

```

locale cdclNOT-merge-bj-learn-ops =
  dpll-state trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT +
  decide-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT +
  forget-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT forget-cond +
  propagate-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT propagate-conds
for
  trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
  clauses :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clsNOT remove-clsNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  propagate-conds :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  bool and
  forget-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool +
fixes backjump-l-cond :: 'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  bool
begin
inductive backjump-l where
backjump-l: trail S = F' @ Marked K () # F
   $\Rightarrow$  no-dup (trail S)
   $\Rightarrow$  T  $\sim$  prepend-trail (Propagated L ()) (reduce-trail-toNOT F (add-clsNOT (C' + {#L#}) S))
   $\Rightarrow$  C  $\in$  # clauses S
   $\Rightarrow$  trail S  $\models_{as}$  CNot C
   $\Rightarrow$  undefined-lit F L
   $\Rightarrow$  atm-of L  $\in$  atms-of-msu (clauses S)  $\cup$  atm-of ' (lits-of (trail S))
   $\Rightarrow$  clauses S  $\models_{pm}$  C' + {#L#}
   $\Rightarrow$  F  $\models_{as}$  CNot C'
   $\Rightarrow$  backjump-l-cond C' L T
   $\Rightarrow$  backjump-l S T
inductive-cases backjump-lE: backjump-l S T

inductive cdclNOT-merged-bj-learn :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool for S :: 'st where
cdclNOT-merged-bj-learn-decideNOT: decideNOT S S'  $\Rightarrow$  cdclNOT-merged-bj-learn S S' |
cdclNOT-merged-bj-learn-propagateNOT: propagateNOT S S'  $\Rightarrow$  cdclNOT-merged-bj-learn S S' |
cdclNOT-merged-bj-learn-backjump-l: backjump-l S S'  $\Rightarrow$  cdclNOT-merged-bj-learn S S' |
cdclNOT-merged-bj-learn-forgetNOT: forgetNOT S S'  $\Rightarrow$  cdclNOT-merged-bj-learn S S'

lemma cdclNOT-merged-bj-learn-no-dup-inv:
  cdclNOT-merged-bj-learn S T  $\Rightarrow$  no-dup (trail S)  $\Rightarrow$  no-dup (trail T)
apply (induction rule: cdclNOT-merged-bj-learn.induct)
  using defined-lit-map apply fastforce
  using defined-lit-map apply fastforce
  apply (force simp: defined-lit-map elim!: backjump-lE)[]
using forgetNOT.sims apply auto[1]
done
end

locale cdclNOT-merge-bj-learn-proxy =
  cdclNOT-merge-bj-learn-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT
  propagate-conds forget-conds  $\lambda C$  L S. backjump-l-cond C L S  $\wedge$  distinct-mset (C + {#L#})
   $\wedge$   $\neg$ tautology (C + {#L#})
for
  trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
  clauses :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and

```

$add_cls_{NOT} \text{ remove_cls}_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st \text{ and}$
 $propagate_conds :: ('v, unit, unit) \text{ marked_lit} \Rightarrow 'st \Rightarrow bool \text{ and}$
 $forget_conds :: 'v \text{ clause} \Rightarrow 'st \Rightarrow bool \text{ and}$
 $backjump_l_cond :: 'v \text{ clause} \Rightarrow 'v \text{ literal} \Rightarrow 'st \Rightarrow bool +$

fixes

$inv :: 'st \Rightarrow bool$

assumes

$bj_can_jump:$
 $\bigwedge S \ C \ F' \ K \ F \ L.$
 $inv \ S$
 $\implies trail \ S = F' @ Marked \ K \ () \ \# \ F$
 $\implies C \in \# \ clauses \ S$
 $\implies trail \ S \models_{as} CNot \ C$
 $\implies undefined_lit \ F \ L$
 $\implies atm_of \ L \in atms_of_msu \ (clauses \ S) \cup atm_of \ ' \ (lits_of \ (F' @ Marked \ K \ () \ \# \ F))$
 $\implies clauses \ S \models_{pm} C' + \{\#L\# \}$
 $\implies F \models_{as} CNot \ C'$
 $\implies \neg no_step \ backjump_l \ S \text{ and}$
 $cdcl_merged_inv: \bigwedge S \ T. \ cdcl_{NOT}\text{-merged-}bj\text{-learn} \ S \ T \implies inv \ S \implies inv \ T$

begin

abbreviation $backjump_conds$ **where**
 $backjump_conds \equiv \lambda C \ L \ -. \ distinct_mset \ (C + \{\#L\# \}) \wedge \neg tautology \ (C + \{\#L\# \})$

sublocale $dpll_with_backjumping_ops \ trail \ clauses \ prepend_trail \ tl_trail \ add_cls_{NOT} \ remove_cls_{NOT}$
 $propagate_conds \ inv \ backjump_conds$

proof ($unfold_locales, \ goal_cases$)

case 1

{ fix $S \ S'$

assume $bj: backjump_l \ S \ S' \text{ and } no_dup \ (trail \ S)$

then obtain $F' \ K \ F \ L \ C' \ C$ **where**
 $S': S' \sim prepend_trail \ (Propagated \ L \ ()) \ (reduce_trail_to_{NOT} \ F$
 $(tl_trail(add_cls_{NOT} \ (C' + \{\#L\# \}) \ S)))$
and
 $tr_S: trail \ S = F' @ Marked \ K \ () \ \# \ F \text{ and}$
 $C: C \in \# \ clauses \ S \text{ and}$
 $tr_S_C: trail \ S \models_{as} CNot \ C \text{ and}$
 $undef_L: undefined_lit \ F \ L \text{ and}$
 $atm_L: atm_of \ L \in atms_of_msu \ (clauses \ S) \cup atm_of \ ' \ lits_of \ (trail \ S) \text{ and}$
 $cls_S_C': clauses \ S \models_{pm} C' + \{\#L\# \} \text{ and}$
 $F_C': F \models_{as} CNot \ C' \text{ and}$
 $dist: distinct_mset \ (C' + \{\#L\# \}) \text{ and}$
 $not_tauto: \neg tautology \ (C' + \{\#L\# \})$
by ($elim \ backjump_lE$) $simp$

have $\exists S'. \ backjumping_ops.backjump \ trail \ clauses \ prepend_trail \ tl_trail \ backjump_conds \ S \ S'$

apply $rule$

apply ($rule \ backjumping_ops.backjump.intros$)

apply $unfold_locales$

using tr_S **apply** $simp$

apply ($rule \ state_eq_{NOT}\text{-ref}$)

using C **apply** $simp$

using tr_S_C **apply** $simp$

using $undef_L$ **apply** $simp$

using atm_L **apply** $simp$

using cls_S_C' **apply** $simp$

```

    using F-C' apply simp
    using dist not-tauto apply simp
    done
  } note H = this(1)
then show ?case using 1 bj-can-jump by meson
qed

end

locale cdclNOT-merge-bj-learn-proxy2 =
  cdclNOT-merge-bj-learn-proxy trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
  propagate-conds forget-conds backjump-l-cond inv
for
  trail :: 'st ⇒ ('v, unit, unit) marked-lits and
  clauses :: 'st ⇒ 'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit ⇒ 'st ⇒ 'st and
  tl-trail :: 'st ⇒ 'st and
  add-clNOT remove-clNOT:: 'v clause ⇒ 'st ⇒ 'st and
  propagate-conds :: ('v, unit, unit) marked-lit ⇒ 'st ⇒ bool and
  inv :: 'st ⇒ bool and
  forget-conds :: 'v clause ⇒ 'st ⇒ bool and
  backjump-l-cond :: 'v clause ⇒ 'v literal ⇒ 'st ⇒ bool
begin

sublocale conflict-driven-clause-learning-ops trail clauses prepend-trail tl-trail add-clNOT
  remove-clNOT propagate-conds inv backjump-conds λC -. distinct-mset C ∧ ¬tautology C
  forget-conds
by unfold-locales
end

locale cdclNOT-merge-bj-learn =
  cdclNOT-merge-bj-learn-proxy2 trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
  propagate-conds inv forget-conds backjump-l-cond
for
  trail :: 'st ⇒ ('v, unit, unit) marked-lits and
  clauses :: 'st ⇒ 'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit ⇒ 'st ⇒ 'st and
  tl-trail :: 'st ⇒ 'st and
  add-clNOT remove-clNOT:: 'v clause ⇒ 'st ⇒ 'st and
  propagate-conds :: ('v, unit, unit) marked-lit ⇒ 'st ⇒ bool and
  inv :: 'st ⇒ bool and
  forget-conds :: 'v clause ⇒ 'st ⇒ bool and
  backjump-l-cond :: 'v clause ⇒ 'v literal ⇒ 'st ⇒ bool +
assumes
  dpll-bj-inv:  $\bigwedge S T. \text{dpll-bj } S T \implies \text{inv } S \implies \text{inv } T$  and
  learn-inv:  $\bigwedge S T. \text{learn } S T \implies \text{inv } S \implies \text{inv } T$ 
begin

interpretation cdclNOT:
  conflict-driven-clause-learning trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
  propagate-conds inv backjump-conds λC -. distinct-mset C ∧ ¬tautology C forget-conds
apply unfold-locales
apply (simp only: cdclNOT.simps)
using cdclNOT-merged-bj-learn-forgetNOT cdcl-merged-inv learn-inv
by (auto simp add: cdclNOT.simps dpll-bj-inv)

```

lemma *backjump-l-learn-backjump*:

assumes *bt*: *backjump-l S T* **and** *inv*: *inv S* **and** *n-d*: *no-dup (trail S)*

shows $\exists C' L. \text{learn } S \text{ (add-cl}_{NOT} (C' + \{\#L\#\}) S)$

$\wedge \text{backjump (add-cl}_{NOT} (C' + \{\#L\#\}) S) T$

$\wedge \text{atms-of } (C' + \{\#L\#\}) \subseteq \text{atms-of-msu (clauses } S) \cup \text{atm-of ' (lits-of (trail } S))$

proof –

obtain *C F' K F L l C'* **where**

tr-S: *trail S = F' @ Marked K () # F* **and**

T: *T ~ prepend-trail (Propagated L l) (reduce-trail-to_{NOT} F (add-cl}_{NOT} (C' + \{\#L\#\}) S))* **and**

C-cls-S: *C ∈ # clauses S* **and**

tr-S-CNot-C: *trail S ⊨_{as} CNot C* **and**

undef: *undefined-lit F L* **and**

atm-L: *atm-of L ∈ atms-of-msu (clauses S) ∪ atm-of ' (lits-of (trail S))* **and**

clss-C: *clauses S ⊨_{pm} C' + \{\#L\#\}* **and**

F ⊨_{as} CNot C' **and**

distinct: *distinct-mset (C' + \{\#L\#\})* **and**

not-tauto: $\neg \text{tautology } (C' + \{\#L\\#)$

using *bt inv* **by** (*elim backjump-lE*) *simp*

have *atms-C'*: *atms-of C' ⊆ atm-of ' (lits-of F)*

proof –

obtain *ll* :: *'v ⇒ ('v literal ⇒ 'v) ⇒ 'v literal set ⇒ 'v literal* **where**

$\forall v f L. v \notin f \text{ ' } L \vee v = f (ll \ v \ f \ L) \wedge ll \ v \ f \ L \in L$

by *moura*

then show *?thesis unfolding tr-S*

by (*metis (no-types) (F ⊨_{as} CNot C') atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set*

atms-of-def in-CNot-implies-uminus(2) mem-set-mset-iff subsetI)

qed

then have *atms-of (C' + \{\#L\#\}) ⊆ atms-of-msu (clauses S) ∪ atm-of ' (lits-of (trail S))*

using *atm-L tr-S* **by** *auto*

moreover have *learn*: *learn S (add-cl}_{NOT} (C' + \{\#L\#\}) S)*

apply (*rule learn.intros*)

apply (*rule clss-C*)

using *atms-C' atm-L* **apply** (*fastforce simp add: tr-S in-plus-implies-atm-of-on-atms-of-ms*)[]

apply *standard*

apply (*rule distinct*)

apply (*rule not-tauto*)

apply *simp*

done

moreover have *bj*: *backjump (add-cl}_{NOT} (C' + \{\#L\#\}) S) T*

apply (*rule backjump.intros*)

using $(F \models_{as} CNot C')$ *C-cls-S tr-S-CNot-C undef T distinct not-tauto n-d*

by (*auto simp: tr-S state-eq_{NOT}-def simp del: state-simp_{NOT}*)

ultimately show *?thesis* **by** *auto*

qed

lemma *cdcl_{NOT}-merged-bj-learn-is-tranclp-cdcl_{NOT}*:

cdcl_{NOT}-merged-bj-learn S T ⇒ inv S ⇒ no-dup (trail S) ⇒ cdcl_{NOT}^{++} S T

proof (*induction rule: cdcl_{NOT}-merged-bj-learn.induct*)

case (*cdcl_{NOT}-merged-bj-learn-decide_{NOT} T*)

then have *cdcl_{NOT} S T*

using *bj-decide_{NOT} cdcl_{NOT}.simps* **by** *fastforce*

then show *?case* **by** *auto*

next

case (*cdcl_{NOT}-merged-bj-learn-propagate_{NOT} T*)

```

then have  $cdcl_{NOT} S T$ 
  using  $bj-propagate_{NOT} cdcl_{NOT}.simps$  by fastforce
then show ?case by auto
next
case ( $cdcl_{NOT}$ -merged- $bj$ -learn-forget $_{NOT} T$ )
then have  $cdcl_{NOT} S T$ 
  using  $c-forget_{NOT}$  by blast
then show ?case by auto
next
case ( $cdcl_{NOT}$ -merged- $bj$ -learn-backjump- $l T$ ) note  $bt = this(1)$  and  $inv = this(2)$  and
   $n-d = this(3)$ 
obtain  $C' :: 'v$  literal multiset and  $L :: 'v$  literal where
   $f3: learn S (add-cls_{NOT} (C' + \{\#L\# \}) S) \wedge$ 
   $backjump (add-cls_{NOT} (C' + \{\#L\# \}) S) T \wedge$ 
   $atms-of (C' + \{\#L\# \}) \subseteq atms-of-msu (clauses S) \cup atm-of \text{ ' } lits-of (trail S)$ 
  using  $n-d$  backjump- $l$ -learn-backjump[ $OF bt inv$ ] by blast
then have  $f4: cdcl_{NOT} S (add-cls_{NOT} (C' + \{\#L\# \}) S)$ 
  using  $n-d$   $c$ -learn by blast
have  $cdcl_{NOT} (add-cls_{NOT} (C' + \{\#L\# \}) S) T$ 
  using  $f3$   $n-d$   $bj$ -backjump  $c$ -dpll- $bj$  by blast
then show ?case
  using  $f4$  by (meson tranclp.r-into-trancl tranclp.trancl-into-trancl)
qed

lemma  $rtranclp$ - $cdcl_{NOT}$ -merged- $bj$ -learn-is- $rtranclp$ - $cdcl_{NOT}$ -and- $inv$ :
 $cdcl_{NOT}$ -merged- $bj$ -learn $^{**} S T \implies inv S \implies no-dup (trail S) \implies cdcl_{NOT}^{**} S T \wedge inv T$ 
proof (induction rule:  $rtranclp$ -induct)
case base
then show ?case by auto
next
case (step  $T U$ ) note  $st = this(1)$  and  $cdcl_{NOT} = this(2)$  and  $IH = this(3)[OF this(4-)]$  and
   $inv = this(4)$  and  $n-d = this(5)$ 
have  $cdcl_{NOT}^{**} T U$ 
  using  $cdcl_{NOT}$ -merged- $bj$ -learn-is- $rtranclp$ - $cdcl_{NOT}$ [ $OF cdcl_{NOT}$ ]  $IH$ 
   $cdcl_{NOT}.rtranclp$ - $cdcl_{NOT}$ -no-dup  $inv$   $n-d$  by auto
then have  $cdcl_{NOT}^{**} S U$  using  $IH$  by fastforce
moreover have  $inv U$  using  $n-d$   $IH$   $\langle cdcl_{NOT}^{**} T U \rangle cdcl_{NOT}.rtranclp$ - $cdcl_{NOT}$ - $inv$  by blast
ultimately show ?case using  $st$  by fast
qed

lemma  $rtranclp$ - $cdcl_{NOT}$ -merged- $bj$ -learn-is- $rtranclp$ - $cdcl_{NOT}$ :
 $cdcl_{NOT}$ -merged- $bj$ -learn $^{**} S T \implies inv S \implies no-dup (trail S) \implies cdcl_{NOT}^{**} S T$ 
using  $rtranclp$ - $cdcl_{NOT}$ -merged- $bj$ -learn-is- $rtranclp$ - $cdcl_{NOT}$ -and- $inv$  by blast

lemma  $rtranclp$ - $cdcl_{NOT}$ -merged- $bj$ -learn- $inv$ :
 $cdcl_{NOT}$ -merged- $bj$ -learn $^{**} S T \implies inv S \implies no-dup (trail S) \implies inv T$ 
using  $rtranclp$ - $cdcl_{NOT}$ -merged- $bj$ -learn-is- $rtranclp$ - $cdcl_{NOT}$ -and- $inv$  by blast

definition  $\mu_C' :: 'v$  literal multiset set  $\Rightarrow 'st \Rightarrow nat$  where
 $\mu_C' A T \equiv \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight T)$ 

definition  $\mu_{CDCL}'$ -merged  $:: 'v$  literal multiset set  $\Rightarrow 'st \Rightarrow nat$  where
 $\mu_{CDCL}'$ -merged  $A T \equiv$ 
 $((2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A)) - \mu_C' A T) * 2 + card (set-mset (clauses T))$ 

```


lemma $cdcl_{NOT}$ -decreasing-measure':

assumes

$cdcl_{NOT}$ -merged-bj-learn S T **and**

inv : inv S **and**

atm -clss: $atms$ -of- msu ($clauses$ S) \subseteq $atms$ -of- ms A **and**

atm -trail: atm -of ' $lits$ -of ($trail$ S) \subseteq $atms$ -of- ms A **and**

n -d: no -dup ($trail$ S) **and**

fin - A : $finite$ A

shows μ_{CDCL}' -merged A T $<$ μ_{CDCL}' -merged A S

using $assms(1)$

proof *induction*

case ($cdcl_{NOT}$ -merged-bj-learn-decide $_{NOT}$ T)

have $clauses$ $S = clauses$ T

using $cdcl_{NOT}$ -merged-bj-learn-decide $_{NOT}$. $hyps$ **by** *auto*

moreover **have**

$(2 + card (atms$ -of- ms $A)) \wedge (1 + card (atms$ -of- ms $A))$
 $- \mu_C (1 + card (atms$ -of- ms $A)) (2 + card (atms$ -of- ms $A)) (trail$ -weight $T)$
 $< (2 + card (atms$ -of- ms $A)) \wedge (1 + card (atms$ -of- ms $A))$
 $- \mu_C (1 + card (atms$ -of- ms $A)) (2 + card (atms$ -of- ms $A)) (trail$ -weight $S)$

apply (*rule* $dpll$ -bj-trail-mes-decreasing-prop)

using $cdcl_{NOT}$ -merged-bj-learn-decide $_{NOT}$ fin - A atm -clss atm -trail n -d inv

by (*simp*-all add : bj -decide $_{NOT}$ $cdcl_{NOT}$ -merged-bj-learn-decide $_{NOT}$. $hyps$)

ultimately show $?case$

unfolding μ_{CDCL}' -merged-def μ_C' -def **by** *simp*

next

case ($cdcl_{NOT}$ -merged-bj-learn-propagate $_{NOT}$ T)

have $clauses$ $S = clauses$ T

using $cdcl_{NOT}$ -merged-bj-learn-propagate $_{NOT}$. $hyps$

by (*simp* add : bj -propagate $_{NOT}$ inv $dpll$ -bj-clauses)

moreover **have**

$(2 + card (atms$ -of- ms $A)) \wedge (1 + card (atms$ -of- ms $A))$
 $- \mu_C (1 + card (atms$ -of- ms $A)) (2 + card (atms$ -of- ms $A)) (trail$ -weight $T)$
 $< (2 + card (atms$ -of- ms $A)) \wedge (1 + card (atms$ -of- ms $A))$
 $- \mu_C (1 + card (atms$ -of- ms $A)) (2 + card (atms$ -of- ms $A)) (trail$ -weight $S)$

apply (*rule* $dpll$ -bj-trail-mes-decreasing-prop)

using inv n -d atm -clss atm -trail fin - A **by** (*simp*-all add : bj -propagate $_{NOT}$

$cdcl_{NOT}$ -merged-bj-learn-propagate $_{NOT}$. $hyps$)

ultimately show $?case$

unfolding μ_{CDCL}' -merged-def μ_C' -def **by** *simp*

next

case ($cdcl_{NOT}$ -merged-bj-learn-forget $_{NOT}$ T)

have $card (set$ -mset ($clauses$ T)) $<$ $card (set$ -mset ($clauses$ S))

using $\langle forget_{NOT} S T \rangle$ **by** (*metis* $card$ -Diff1-less

$cdcl_{NOT}$ -merged-bj-learn-forget $_{NOT}$. $hyps$ $clauses$ -remove-cls $_{NOT}$ $finite$ -set-mset $forgetE$

mem -set-mset-iff $order$ -refl set -mset-minus-replicate-mset(1) $state$ -eq $_{NOT}$ -clauses)

moreover

have $trail$ $S = trail$ T

using $\langle forget_{NOT} S T \rangle$ **by** (*auto* $elim$: $forgetE$)

then **have**

$(2 + card (atms$ -of- ms $A)) \wedge (1 + card (atms$ -of- ms $A))$
 $- \mu_C (1 + card (atms$ -of- ms $A)) (2 + card (atms$ -of- ms $A)) (trail$ -weight $T)$
 $= (2 + card (atms$ -of- ms $A)) \wedge (1 + card (atms$ -of- ms $A))$
 $- \mu_C (1 + card (atms$ -of- ms $A)) (2 + card (atms$ -of- ms $A)) (trail$ -weight $S)$

by *auto*

ultimately show $?case$

unfolding μ_{CDCL}' -merged-def μ_C' -def **by** *simp*
next
case ($cdcl_{NOT}$ -merged-bj-learn-backjump-l T) **note** $bj-l = this(1)$
obtain $C' L$ **where**
 $learn$: $learn\ S\ (add-cl_{NOT}\ (C' + \{\#L\# \})\ S)$ **and**
 bj : $backjump\ (add-cl_{NOT}\ (C' + \{\#L\# \})\ S)\ T$ **and**
 $atms-C$: $atms-of\ (C' + \{\#L\# \}) \subseteq atms-of-msu\ (clauses\ S) \cup atm-of\ ' (lits-of\ (trail\ S))$
using $bj-l\ inv\ backjump-l-learn-backjump\ n-d\ atm-clss\ atm-trail$ **by** *blast*
have $card-T-S$: $card\ (set-mset\ (clauses\ T)) \leq 1 + card\ (set-mset\ (clauses\ S))$
using $bj-l\ inv$ **by** (*force elim!*: $backjump-lE$ *simp*: $card-insert-if$)
have
 $((2 + card\ (atms-of-ms\ A)) \wedge (1 + card\ (atms-of-ms\ A))$
 $\quad - \mu_C\ (1 + card\ (atms-of-ms\ A))\ (2 + card\ (atms-of-ms\ A))\ (trail-weight\ T))$
 $< ((2 + card\ (atms-of-ms\ A)) \wedge (1 + card\ (atms-of-ms\ A))$
 $\quad - \mu_C\ (1 + card\ (atms-of-ms\ A))\ (2 + card\ (atms-of-ms\ A))$
 $\quad (trail-weight\ (add-cl_{NOT}\ (C' + \{\#L\# \})\ S)))$
apply (*rule dpll-bj-trail-mes-decreasing-prop*)
using $bj\ bj-backjump$ **apply** *blast*
using $cdcl_{NOT}.c-learn\ cdcl_{NOT}.cdcl_{NOT}-inv\ inv\ learn$ **apply** *blast*
using $atms-C\ atm-clss\ atm-trail\ n-d\ clauses-add-cl_{NOT}$ **apply** *simp* **apply** *fast*
using $atm-trail\ n-d$ **apply** *simp*
apply (*simp add: n-d*)
using $fin-A$ **apply** *simp*
done
then have $((2 + card\ (atms-of-ms\ A)) \wedge (1 + card\ (atms-of-ms\ A))$
 $\quad - \mu_C\ (1 + card\ (atms-of-ms\ A))\ (2 + card\ (atms-of-ms\ A))\ (trail-weight\ T))$
 $< ((2 + card\ (atms-of-ms\ A)) \wedge (1 + card\ (atms-of-ms\ A))$
 $\quad - \mu_C\ (1 + card\ (atms-of-ms\ A))\ (2 + card\ (atms-of-ms\ A))\ (trail-weight\ S))$
using $n-d$ **by** *auto*
then show *?case*
using $card-T-S$ **unfolding** μ_{CDCL}' -merged-def μ_C' -def **by** *linarith*
qed

lemma $wf-cdcl_{NOT}$ -merged-bj-learn:

assumes

$fin-A$: *finite A*

shows $wf\ \{(T, S)\}$.

$(inv\ S \wedge atms-of-msu\ (clauses\ S) \subseteq atms-of-ms\ A \wedge atm-of\ ' lits-of\ (trail\ S) \subseteq atms-of-ms\ A$
 $\wedge no-dup\ (trail\ S))$

$\wedge cdcl_{NOT}$ -merged-bj-learn $S\ T\}$

apply (*rule wfP-if-measure[of - - μ_{CDCL}' -merged A]*)

using $cdcl_{NOT}$ -decreasing-measure' $fin-A$ **by** *simp*

lemma $trancpl-cdcl_{NOT}$ - $cdcl_{NOT}$ - $trancpl$:

assumes

$cdcl_{NOT}$ -merged-bj-learn⁺⁺ $S\ T$ **and**

inv : $inv\ S$ **and**

$atm-clss$: $atms-of-msu\ (clauses\ S) \subseteq atms-of-ms\ A$ **and**

$atm-trail$: $atm-of\ ' lits-of\ (trail\ S) \subseteq atms-of-ms\ A$ **and**

$n-d$: $no-dup\ (trail\ S)$ **and**

$fin-A[simp]$: *finite A*

shows $(T, S) \in \{(T, S)\}$.

$(inv\ S \wedge atms-of-msu\ (clauses\ S) \subseteq atms-of-ms\ A \wedge atm-of\ ' lits-of\ (trail\ S) \subseteq atms-of-ms\ A$
 $\wedge no-dup\ (trail\ S))$

$\wedge cdcl_{NOT}$ -merged-bj-learn $S\ T\}^+ (is - \in ?P^+)$

```

using assms(1)
proof (induction rule: tranclp-induct)
  case base
  then show ?case using n-d atm-clss atm-trail inv by auto
next
  case (step T U) note st = this(1) and cdclNOT = this(2) and IH = this(3)
  have cdclNOT** S T
    apply (rule rtranclp-cdclNOT-merged-bj-learn-is-rtranclp-cdclNOT)
    using st cdclNOT inv n-d atm-clss atm-trail inv by auto
  have inv T
    apply (rule rtranclp-cdclNOT-merged-bj-learn-inv)
    using inv st cdclNOT n-d atm-clss atm-trail inv by auto
  moreover have atms-of-msu (clauses T) ⊆ atms-of-ms A
    using cdclNOT.rtranclp-cdclNOT-trail-clauses-bound[OF <cdclNOT** S T> inv n-d atm-clss atm-trail]
    by fast
  moreover have atm-of ‘ (lits-of (trail T)) ⊆ atms-of-ms A
    using cdclNOT.rtranclp-cdclNOT-trail-clauses-bound[OF <cdclNOT** S T> inv n-d atm-clss atm-trail]
    by fast
  moreover have no-dup (trail T)
    using cdclNOT.rtranclp-cdclNOT-no-dup[OF <cdclNOT** S T> inv n-d] by fast
  ultimately have (U, T) ∈ ?P
    using cdclNOT by auto
  then show ?case using IH by (simp add: trancl-into-trancl2)
qed

```

```

lemma wf-tranclp-cdclNOT-merged-bj-learn:
  assumes finite A
  shows wf {(T, S).
    (inv S ∧ atms-of-msu (clauses S) ⊆ atms-of-ms A ∧ atm-of ‘ lits-of (trail S) ⊆ atms-of-ms A
     $\wedge$  no-dup (trail S))
     $\wedge$  cdclNOT-merged-bj-learn++ S T}
  apply (rule wf-subset)
  apply (rule wf-trancl[OF wf-cdclNOT-merged-bj-learn])
  using assms apply simp
  using tranclp-cdclNOT-cdclNOT-tranclp[OF - - - - <finite A>] by auto

```

```

lemma backjump-no-step-backjump-l:
  backjump S T  $\implies$  inv S  $\implies$   $\neg$ no-step backjump-l S
  apply (elim backjumpE)
  apply (rule bj-can-jump)
  apply auto[7]
by blast

```

```

lemma cdclNOT-merged-bj-learn-final-state:
  fixes A :: 'v literal multiset set and S T :: 'st
  assumes
    n-s: no-step cdclNOT-merged-bj-learn S and
    atms-S: atms-of-msu (clauses S) ⊆ atms-of-ms A and
    atms-trail: atm-of ‘ lits-of (trail S) ⊆ atms-of-ms A and
    n-d: no-dup (trail S) and
    finite A and
    inv: inv S and
    decomp: all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S))
  shows unsatisfiable (set-mset (clauses S))
     $\vee$  (trail S  $\models_{asm}$  clauses S  $\wedge$  satisfiable (set-mset (clauses S)))

```

```

proof –
  let ?N = set-mset (clauses S)
  let ?M = trail S
  consider
    (sat) satisfiable ?N and ?M  $\models_{as}$  ?N
  | (sat') satisfiable ?N and  $\neg$  ?M  $\models_{as}$  ?N
  | (unsat) unsatisfiable ?N
  by auto
then show ?thesis
proof cases
  case sat' note sat = this(1) and M = this(2)
  obtain C where C  $\in$  ?N and  $\neg$  ?M  $\models_a$  C using M unfolding true-annots-def by auto
  obtain I :: 'v literal set where
    I  $\models_s$  ?N and
    cons: consistent-interp I and
    tot: total-over-m I ?N and
    atm-I-N: atm-of 'I  $\subseteq$  atms-of-ms ?N
    using sat unfolding satisfiable-def-min by auto
  let ?I = I  $\cup$  {P | P. P  $\in$  lits-of ?M  $\wedge$  atm-of P  $\notin$  atm-of 'I}
  let ?O = { {#lit-of L#} | L. is-marked L  $\wedge$  L  $\in$  set ?M  $\wedge$  atm-of (lit-of L)  $\notin$  atms-of-ms ?N }
  have cons-I': consistent-interp ?I
    using cons using no-dup ?M unfolding consistent-interp-def
    by (auto simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set lits-of-def
      dest!: no-dup-cannot-not-lit-and-uminus)
  have tot-I': total-over-m ?I (?N  $\cup$  ( $\lambda a.$  {#lit-of a#})) ' set ?M)
    using tot atms-of-s-def unfolding total-over-m-def total-over-set-def
    by fastforce
  have {P | P. P  $\in$  lits-of ?M  $\wedge$  atm-of P  $\notin$  atm-of 'I}  $\models_s$  ?O
    using  $\langle I \models_s ?N \rangle$  atm-I-N by (auto simp add: atm-of-eq-atm-of true-clss-def lits-of-def)
  then have I'-N: ?I  $\models_s$  ?N  $\cup$  ?O
    using  $\langle I \models_s ?N \rangle$  true-clss-union-increase by force
  have tot': total-over-m ?I (?N  $\cup$  ?O)
    using atm-I-N tot unfolding total-over-m-def total-over-set-def
    by (force simp: image-iff lits-of-def dest!: is-marked-ex-Marked)

  have atms-N-M: atms-of-ms ?N  $\subseteq$  atm-of ' lits-of ?M
  proof (rule ccontr)
    assume  $\neg$  ?thesis
    then obtain l :: 'v where
      l-N: l  $\in$  atms-of-ms ?N and
      l-M: l  $\notin$  atm-of ' lits-of ?M
    by auto
    have undefined-lit ?M (Pos l)
      using l-M by (metis Marked-Propagated-in-iff-in-lits-of
        atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set literal.sel(1))
    have decideNOT S (prepend-trail (Marked (Pos l) ()) S)
      by (metis undefined-lit ?M (Pos l) decideNOT.intros l-N literal.sel(1)
        state-eqNOT-ref)
    then show False
      using cdclNOT-merged-bj-learn-decideNOT n-s by blast
  qed

have ?M  $\models_{as}$  CNot C
  by (metis atms-N-M  $\langle C \in ?N \rangle$   $\langle \neg$  ?M  $\models_a$  C  $\rangle$  all-variables-defined-not-imply-cnot
    atms-of-atms-of-ms-mono atms-of-ms-CNot-atms-of atms-of-ms-CNot-atms-of-ms subsetCE)

```



```

qed
have ?N  $\models_p$  image-mset uminus ?C + {#-K#}
  unfolding true-clss-clss-def true-clss-clss-def total-over-m-def
  proof (intro allI impI)
    fix I
    assume
      tot: total-over-set I (atms-of-ms (?N  $\cup$  {image-mset uminus ?C + {#-K#}})) and
      cons: consistent-interp I and
      I  $\models_s$  ?N
    have (K  $\in$  I  $\wedge$  -K  $\notin$  I)  $\vee$  (-K  $\in$  I  $\wedge$  K  $\notin$  I)
      using cons tot unfolding consistent-interp-def by (cases K) auto
    have tot': total-over-set I
      (atm-of 'lit-of ' (set ?M  $\cap$  {L. is-marked L  $\wedge$  L  $\neq$  Marked K ()}))
      using tot by (auto simp add: atms-of-uminus-lit-atm-of-lit-of)
    { fix x :: ('v, unit, unit) marked-lit
      assume
        a3: lit-of x  $\notin$  I and
        a1: x  $\in$  set ?M and
        a4: is-marked x and
        a5: x  $\neq$  Marked K ()
      then have Pos (atm-of (lit-of x))  $\in$  I  $\vee$  Neg (atm-of (lit-of x))  $\in$  I
        using a5 a4 tot' a1 unfolding total-over-set-def atms-of-s-def by blast
      moreover have f6: Neg (atm-of (lit-of x)) = - Pos (atm-of (lit-of x))
        by simp
      ultimately have - lit-of x  $\in$  I
        using f6 a3 by (metis (no-types) atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
          literal.sel(1))
    } note H = this

    have  $\neg I \models_s ?C'$ 
      using  $\langle ?N \cup ?C' \models_{ps} \{\{\#\}\} \rangle$  tot cons  $\langle I \models_s ?N \rangle$ 
      unfolding true-clss-clss-def total-over-m-def
      by (simp add: atms-of-uminus-lit-atm-of-lit-of atms-of-ms-single-image-atm-of-lit-of)
    then show I  $\models$  image-mset uminus ?C + {#-K#}
      unfolding true-clss-def true-clss-def Bex-mset-def
      using  $\langle (K \in I \wedge -K \notin I) \vee (-K \in I \wedge K \notin I) \rangle$ 
      by (auto dest!: H)
  qed

moreover have F  $\models_{as}$  CNot (image-mset uminus ?C)
  using nm unfolding true-annots-def CNot-def M-K by (auto simp add: lits-of-def)
ultimately have False
  using bj-can-jump[of S F' K F C -K
    image-mset uminus (image-mset lit-of {# L :# mset ?M. is-marked L  $\wedge$  L  $\neq$  Marked K ()#})]
     $\langle C \in ?N \rangle$  n-s  $\langle ?M \models_{as} CNot C \rangle$  bj-backjump inv unfolding M-K
  by (auto simp: cdclNOT-merged-bj-learn.simps)
then show ?thesis by fast
qed auto
qed

lemma full-cdclNOT-merged-bj-learn-final-state:
  fixes A :: 'v literal multiset set and S T :: 'st
  assumes
    full: full cdclNOT-merged-bj-learn S T and
    atms-S: atms-of-msu (clauses S)  $\subseteq$  atms-of-ms A and
    atms-trail: atm-of 'lits-of (trail S)  $\subseteq$  atms-of-ms A and

```

n-d: *no-dup* (*trail S*) **and**
finite A **and**
inv: *inv S* **and**
decomp: *all-decomposition-implies-m* (*clauses S*) (*get-all-marked-decomposition* (*trail S*))
shows *unsatisfiable* (*set-mset* (*clauses T*))
 \vee (*trail T* \models_{asm} *clauses T* \wedge *satisfiable* (*set-mset* (*clauses T*)))
proof –
have *st*: *cdcl_{NOT}-merged-bj-learn^{**} S T* **and** *n-s*: *no-step cdcl_{NOT}-merged-bj-learn T*
using *full unfolding full-def* **by** *blast+*
then have *st*: *cdcl_{NOT}^{**} S T*
using *inv rtrancpl-cdcl_{NOT}-merged-bj-learn-is-rtrancpl-cdcl_{NOT}-and-inv n-d* **by** *auto*
have *atms-of-msu* (*clauses T*) \subseteq *atms-of-ms A* **and** *atm-of* ‘*lits-of* (*trail T*) \subseteq *atms-of-ms A*
using *cdcl_{NOT}.rtrancpl-cdcl_{NOT}-trail-clauses-bound*[*OF st inv n-d atms-S atms-trail*] **by** *blast+*
moreover have *no-dup* (*trail T*)
using *cdcl_{NOT}.rtrancpl-cdcl_{NOT}-no-dup inv n-d st* **by** *blast*
moreover have *inv T*
using *cdcl_{NOT}.rtrancpl-cdcl_{NOT}-inv inv st* **by** *blast*
moreover have *all-decomposition-implies-m* (*clauses T*) (*get-all-marked-decomposition* (*trail T*))
using *cdcl_{NOT}.rtrancpl-cdcl_{NOT}-all-decomposition-implies inv st decomp n-d* **by** *blast*
ultimately show *?thesis*
using *cdcl_{NOT}-merged-bj-learn-final-state*[*of T A*] (*finite A*) *n-s* **by** *fast*
qed
end

14.8.1 Instantiations

locale *cdcl_{NOT}-with-backtrack-and-restarts* =
conflict-driven-clause-learning-learning-before-backjump-only-distinct-learnt trail clauses
prepend-trail tl-trail add-cl_s_{NOT} remove-cl_s_{NOT} propagate-con_s inv backjump-con_s
learn-restrictions forget-restrictions
for
trail :: ‘*st* \Rightarrow (*v*::*linorder*, *unit*, *unit*) marked-lits **and**
clauses :: ‘*st* \Rightarrow ‘*v*::*linorder* *clauses* **and**
prepend-trail :: (*v*, *unit*, *unit*) marked-lit \Rightarrow ‘*st* \Rightarrow ‘*st* **and**
tl-trail :: ‘*st* \Rightarrow ‘*st* **and**
add-cl_s_{NOT} remove-cl_s_{NOT} :: ‘*v* *clause* \Rightarrow ‘*st* \Rightarrow ‘*st* **and**
propagate-con_s :: (*v*, *unit*, *unit*) marked-lit \Rightarrow ‘*st* \Rightarrow *bool* **and**
inv :: ‘*st* \Rightarrow *bool* **and**
backjump-con_s :: ‘*v* *clause* \Rightarrow ‘*v* *literal* \Rightarrow ‘*st* \Rightarrow ‘*st* \Rightarrow *bool* **and**
learn-restrictions forget-restrictions :: ‘*v*::*linorder* *clause* \Rightarrow ‘*st* \Rightarrow *bool*
+
fixes *f* :: *nat* \Rightarrow *nat*
assumes
unbounded: *unbounded f* **and** *f-ge-1*: $\bigwedge n. n \geq 1 \Rightarrow f\ n \geq 1$ **and**
inv-restart: $\bigwedge S\ T. inv\ S \Rightarrow T \sim reduce-trail-to_{NOT} \sqcap S \Rightarrow inv\ T$
begin

lemma *bound-inv-inv*:

assumes
inv S **and**
n-d: *no-dup* (*trail S*) **and**
atms-cl_s-S-A: *atms-of-msu* (*clauses S*) \subseteq *atms-of-ms A* **and**
atms-trail-S-A: *atm-of* ‘*lits-of* (*trail S*) \subseteq *atms-of-ms A* **and**
finite A **and**
cdcl_{NOT}: *cdcl_{NOT} S T*

shows
 $atms\text{-}of\text{-}msu \text{ (clauses } T) \subseteq atms\text{-}of\text{-}ms A$ **and**
 $atm\text{-}of \text{ ' lits-of (trail } T) \subseteq atms\text{-}of\text{-}ms A$ **and**
 $finite A$
proof –
have $cdcl_{NOT} S T$
using $\langle inv S \rangle cdcl_{NOT}$ **by** *linarith*
then have $atms\text{-}of\text{-}msu \text{ (clauses } T) \subseteq atms\text{-}of\text{-}msu \text{ (clauses } S) \cup atm\text{-}of \text{ ' lits-of (trail } S)$
using $\langle inv S \rangle$
by (*meson conflict-driven-clause-learning-ops.cdcl_{NOT}-atms-of-ms-clauses-decreasing*
conflict-driven-clause-learning-ops-axioms n-d)
then show $atms\text{-}of\text{-}msu \text{ (clauses } T) \subseteq atms\text{-}of\text{-}ms A$
using *atms-clss-S-A atms-trail-S-A* **by** *blast*
next
show $atm\text{-}of \text{ ' lits-of (trail } T) \subseteq atms\text{-}of\text{-}ms A$
by (*meson* $\langle inv S \rangle$ *atms-clss-S-A atms-trail-S-A cdcl_{NOT} cdcl_{NOT}-atms-in-trail-in-set n-d*)
next
show $finite A$
using $\langle finite A \rangle$ **by** *simp*
qed
sublocale *cdcl_{NOT}-increasing-restarts-ops* $\lambda S T. T \sim reduce\text{-}trail\text{-}to_{NOT} [] S cdcl_{NOT} f$
 $\lambda A S. atms\text{-}of\text{-}msu \text{ (clauses } S) \subseteq atms\text{-}of\text{-}ms A \wedge atm\text{-}of \text{ ' lits-of (trail } S) \subseteq atms\text{-}of\text{-}ms A \wedge$
 $finite A$
 $\mu_{CDCL}' \lambda S. inv S \wedge no\text{-}dup \text{ (trail } S)$
 $\mu_{CDCL}'\text{-bound}$
apply *unfold-locales*
apply (*simp add: unbounded*)
using *f-ge-1* **apply** *force*
using *bound-inv-inv* **apply** *meson*
apply (*rule cdcl_{NOT}-decreasing-measure'; simp*)
apply (*rule rtrancp-cdcl_{NOT}-μ_{CDCL}'-bound; simp*)
apply (*rule rtrancp-μ_{CDCL}'-bound-decreasing; simp*)
apply *auto[]*
apply *auto[]*
using *cdcl_{NOT}-inv cdcl_{NOT}-no-dup* **apply** *blast*
using *inv-restart* **apply** *auto[]*
done

abbreviation $cdcl_{NOT}\text{-}l$ **where**

$cdcl_{NOT}\text{-}l \equiv$
conflict-driven-clause-learning-ops.cdcl_{NOT} trail clauses prepend-trail tl-trail add-cl_{NOT}
remove-cl_{NOT} propagate-conds (λ- - S T. backjump S T)
 $(\lambda C S. distinct\text{-}mset C \wedge \neg tautology C \wedge learn\text{-}restrictions C S$
 $\wedge (\exists F K F' C' L. trail S = F' @ Marked K () \# F \wedge C = C' + \{\#L\#$
 $\wedge F \models_{as} CNot C' \wedge C' + \{\#L\#\} \notin \# clauses S))$
 $(\lambda C S. \neg (\exists F' F K L. trail S = F' @ Marked K () \# F \wedge F \models_{as} CNot (C - \{\#L\#\}))$
 $\wedge forget\text{-}restrictions C S)$

lemma *cdcl_{NOT}-with-restart-μ_{CDCL}'-le-μ_{CDCL}'-bound:*

assumes

$cdcl_{NOT}: cdcl_{NOT}\text{-}restart (T, a) (V, b)$ **and**

$cdcl_{NOT}\text{-}inv:$

$inv T$

$no\text{-}dup \text{ (trail } T)$ **and**

$bound\text{-}inv:$

$atms\text{-}of\text{-}msu \text{ (clauses } T) \subseteq atms\text{-}of\text{-}ms \ A$
 $atm\text{-}of \text{ ' lits-}of \text{ (trail } T) \subseteq atms\text{-}of\text{-}ms \ A$
 $finite \ A$
shows $\mu_{CDCL}' \ A \ V \leq \mu_{CDCL}'\text{-}bound \ A \ T$
using $cdcl_{NOT}\text{-}inv \ bound\text{-}inv$
proof (*induction rule: $cdcl_{NOT}\text{-}with\text{-}restart\text{-}induct[OF \ cdcl_{NOT}]$*)
case $(1 \ m \ S \ T \ n \ U)$ **note** $U = this(3)$
show $?case$
apply (*rule $rtrancpl\text{-}cdcl_{NOT}\text{-}\mu_{CDCL}'\text{-}bound\text{-}reduce\text{-}trail\text{-}to_{NOT}[of \ S \ T]$*)
using $\langle (cdcl_{NOT} \rightsquigarrow m) \ S \ T \rangle$ **apply** (*fastforce dest!: relpowp-imp-rtrancpl*)
using 1 **by** *auto*
next
case $(2 \ S \ T \ n)$ **note** $full = this(2)$
show $?case$
apply (*rule $rtrancpl\text{-}cdcl_{NOT}\text{-}\mu_{CDCL}'\text{-}bound$*)
using full 2 **unfolding** full1-def **by** force+
qed

lemma $cdcl_{NOT}\text{-}with\text{-}restart\text{-}\mu_{CDCL}'\text{-}bound\text{-}le\text{-}\mu_{CDCL}'\text{-}bound$:
assumes
 $cdcl_{NOT}$: $cdcl_{NOT}\text{-}restart \ (T, \ a) \ (V, \ b)$ **and**
 $cdcl_{NOT}\text{-}inv$:
 $inv \ T$
 $no\text{-}dup \ (trail \ T)$ **and**
 $bound\text{-}inv$:
 $atms\text{-}of\text{-}msu \text{ (clauses } T) \subseteq atms\text{-}of\text{-}ms \ A$
 $atm\text{-}of \text{ ' lits-}of \text{ (trail } T) \subseteq atms\text{-}of\text{-}ms \ A$
 $finite \ A$
shows $\mu_{CDCL}'\text{-}bound \ A \ V \leq \mu_{CDCL}'\text{-}bound \ A \ T$
using $cdcl_{NOT}\text{-}inv \ bound\text{-}inv$
proof (*induction rule: $cdcl_{NOT}\text{-}with\text{-}restart\text{-}induct[OF \ cdcl_{NOT}]$*)
case $(1 \ m \ S \ T \ n \ U)$ **note** $U = this(3)$
have $\mu_{CDCL}'\text{-}bound \ A \ T \leq \mu_{CDCL}'\text{-}bound \ A \ S$
apply (*rule $rtrancpl\text{-}\mu_{CDCL}'\text{-}bound\text{-}decreasing$*)
using $\langle (cdcl_{NOT} \rightsquigarrow m) \ S \ T \rangle$ **apply** (*fastforce dest: relpowp-imp-rtrancpl*)
using 1 **by** *auto*
then show $?case$ **using** U **unfolding** $\mu_{CDCL}'\text{-}bound\text{-}def$ **by** *auto*
next
case $(2 \ S \ T \ n)$ **note** $full = this(2)$
show $?case$
apply (*rule $rtrancpl\text{-}\mu_{CDCL}'\text{-}bound\text{-}decreasing$*)
using full 2 **unfolding** full1-def **by** force+
qed

sublocale $cdcl_{NOT}\text{-}increasing\text{-}restarts \ - \ - \ - \ - \ f$
 $\lambda S \ T. \ T \sim reduce\text{-}trail\text{-}to_{NOT} \ [] \ S$
 $\lambda A \ S. \ atms\text{-}of\text{-}msu \text{ (clauses } S) \subseteq atms\text{-}of\text{-}ms \ A$
 $\wedge atm\text{-}of \text{ ' lits-}of \text{ (trail } S) \subseteq atms\text{-}of\text{-}ms \ A \wedge finite \ A$
 $\mu_{CDCL}' \ cdcl_{NOT}$
 $\lambda S. \ inv \ S \wedge no\text{-}dup \ (trail \ S)$
 $\mu_{CDCL}'\text{-}bound$
apply *unfold-locales*
using $cdcl_{NOT}\text{-}with\text{-}restart\text{-}\mu_{CDCL}'\text{-}le\text{-}\mu_{CDCL}'\text{-}bound$ **apply** *simp*
using $cdcl_{NOT}\text{-}with\text{-}restart\text{-}\mu_{CDCL}'\text{-}bound\text{-}le\text{-}\mu_{CDCL}'\text{-}bound$ **apply** *simp*
done

lemma *cdcl_{NOT}-restart-all-decomposition-implies*:
assumes *cdcl_{NOT}-restart* *S T* **and**
inv (*fst S*) **and**
no-dup (*trail* (*fst S*))
all-decomposition-implies-m (*clauses* (*fst S*)) (*get-all-marked-decomposition* (*trail* (*fst S*)))
shows
all-decomposition-implies-m (*clauses* (*fst T*)) (*get-all-marked-decomposition* (*trail* (*fst T*)))
using *assms* **apply** (*induction*)
using *rtrancpl-cdcl_{NOT}-all-decomposition-implies* **by** (*auto dest!*: *trancpl-into-rtrancpl*
simp: full1-def)

lemma *rtrancpl-cdcl_{NOT}-restart-all-decomposition-implies*:
assumes *cdcl_{NOT}-restart*** *S T* **and**
inv: *inv* (*fst S*) **and**
n-d: *no-dup* (*trail* (*fst S*)) **and**
decomp:
all-decomposition-implies-m (*clauses* (*fst S*)) (*get-all-marked-decomposition* (*trail* (*fst S*)))
shows
all-decomposition-implies-m (*clauses* (*fst T*)) (*get-all-marked-decomposition* (*trail* (*fst T*)))
using *assms*(1)
proof (*induction rule: rtrancpl-induct*)
case *base*
then show *?case* **using** *decomp* **by** *simp*
next
case (*step T u*) **note** *st = this(1)* **and** *r = this(2)* **and** *IH = this(3)*
have *inv* (*fst T*)
using *rtrancpl-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv*[*OF st*] *inv n-d* **by** *blast*
moreover have *no-dup* (*trail* (*fst T*))
using *rtrancpl-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv*[*OF st*] *inv n-d* **by** *blast*
ultimately show *?case*
using *cdcl_{NOT}-restart-all-decomposition-implies* *r IH n-d* **by** *fast*
qed

lemma *cdcl_{NOT}-restart-sat-ext-iff*:
assumes
st: *cdcl_{NOT}-restart* *S T* **and**
n-d: *no-dup* (*trail* (*fst S*)) **and**
inv: *inv* (*fst S*)
shows $I \models_{\text{sextm}} \text{clauses}(\text{fst } S) \longleftrightarrow I \models_{\text{sextm}} \text{clauses}(\text{fst } T)$
using *assms*
proof (*induction*)
case (*restart-step m S T n U*)
then show *?case*
using *rtrancpl-cdcl_{NOT}-bj-sat-ext-iff* *n-d* **by** (*fastforce dest!*: *relpowp-imp-rtrancpl*)
next
case *restart-full*
then show *?case* **using** *rtrancpl-cdcl_{NOT}-bj-sat-ext-iff* **unfolding** *full1-def*
by (*fastforce dest!*: *trancpl-into-rtrancpl*)
qed

lemma *rtrancpl-cdcl_{NOT}-restart-sat-ext-iff*:
assumes
st: *cdcl_{NOT}-restart*** *S T* **and**
n-d: *no-dup* (*trail* (*fst S*)) **and**

inv: *inv* (*fst* *S*)
shows $I \models_{\text{sextm}} \text{clauses } (\text{fst } S) \longleftrightarrow I \models_{\text{sextm}} \text{clauses}(\text{fst } T)$
using *st*
proof (*induction*)
case *base*
then show ?*case* **by** *simp*
next
case (*step* *T U*) **note** *st* = *this*(1) **and** *r* = *this*(2) **and** *IH* = *this*(3)
have *inv* (*fst* *T*)
using *rtranclp-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv*[*OF st*] *inv n-d* **by** *blast* +
moreover **have** *no-dup* (*trail* (*fst* *T*))
using *rtranclp-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv* *rtranclp-cdcl_{NOT}-no-dup* *st inv n-d* **by** *blast*
ultimately show ?*case*
using *cdcl_{NOT}-restart-sat-ext-iff*[*OF r*] *IH* **by** *blast*
qed

theorem *full-cdcl_{NOT}-restart-backjump-final-state*:

fixes *A* :: '*v* literal multiset set **and** *S T* :: '*st*

assumes

full: *full cdcl_{NOT}-restart* (*S*, *n*) (*T*, *m*) **and**

atms-S: *atms-of-msu* (*clauses S*) \subseteq *atms-of-ms A* **and**

atms-trail: *atm-of* '*lits-of* (*trail S*) \subseteq *atms-of-ms A* **and**

n-d: *no-dup* (*trail S*) **and**

fin-A[*simp*]: *finite A* **and**

inv: *inv S* **and**

decomp: *all-decomposition-implies-m* (*clauses S*) (*get-all-marked-decomposition* (*trail S*))

shows *unsatisfiable* (*set-mset* (*clauses S*))

\vee (*lits-of* (*trail T*) \models_{sextm} *clauses S* \wedge *satisfiable* (*set-mset* (*clauses S*)))

proof –

have *st*: *cdcl_{NOT}-restart*** (*S*, *n*) (*T*, *m*) **and**

n-s: *no-step cdcl_{NOT}-restart* (*T*, *m*)

using *full unfolding full-def* **by** *fast+*

have *binv-T*: *atms-of-msu* (*clauses T*) \subseteq *atms-of-ms A* *atm-of* '*lits-of* (*trail T*) \subseteq *atms-of-ms A*

using *rtranclp-cdcl_{NOT}-with-restart-bound-inv*[*OF st*, *of A*] *inv n-d atms-S atms-trail*

by *auto*

moreover **have** *inv-T*: *no-dup* (*trail T*) *inv T*

using *rtranclp-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv*[*OF st*] *inv n-d* **by** *auto*

moreover **have** *all-decomposition-implies-m* (*clauses T*) (*get-all-marked-decomposition* (*trail T*))

using *rtranclp-cdcl_{NOT}-restart-all-decomposition-implies*[*OF st*] *inv n-d*

decomp **by** *auto*

ultimately have *T*: *unsatisfiable* (*set-mset* (*clauses T*))

\vee (*trail T* \models_{asm} *clauses T* \wedge *satisfiable* (*set-mset* (*clauses T*)))

using *no-step-cdcl_{NOT}-restart-no-step-cdcl_{NOT}*[*of* (*T*, *m*) *A*] *n-s*

cdcl_{NOT}-final-state[*of T A*] **unfolding** *cdcl_{NOT}-NOT-all-inv-def* **by** *auto*

have *eq-sat-S-T*: $\bigwedge I. I \models_{\text{sextm}} \text{clauses } S \longleftrightarrow I \models_{\text{sextm}} \text{clauses } T$

using *rtranclp-cdcl_{NOT}-restart-sat-ext-iff*[*OF st*] *inv n-d atms-S*

atms-trail **by** *auto*

have *cons-T*: *consistent-interp* (*lits-of* (*trail T*))

using *inv-T*(1) *distinctconsistent-interp* **by** *blast*

consider

(*unsat*) *unsatisfiable* (*set-mset* (*clauses T*))

| (*sat*) *trail T* \models_{asm} *clauses T* **and** *satisfiable* (*set-mset* (*clauses T*))

using *T* **by** *blast*

then show ?*thesis*

proof *cases*

```

case unsat
then have unsatisfiable (set-mset (clauses S))
  using eq-sat-S-T consistent-true-clss-ext-satisfiable true-clss-imp-true-clss-ext
  unfolding satisfiable-def by blast
then show ?thesis by fast
next
case sat
then have lits-of (trail T)  $\models_{\text{sextm}}$  clauses S
  using rtrancplp-cdclNOT-restart-sat-ext-iff[OF st] inv n-d atms-S
  atms-trail by (auto simp: true-clss-imp-true-clss-ext true-annots-true-clss)
moreover then have satisfiable (set-mset (clauses S))
  using cons-T consistent-true-clss-ext-satisfiable by blast
ultimately show ?thesis by blast
qed
qed
end — end of cdclNOT-with-backtrack-and-restarts locale

locale most-general-cdclNOT =
  dpll-state trail clauses prepend-trail tl-trail add-clNOT remove-clNOT +
  propagate-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT propagate-conds +
  backjumping-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT  $\lambda$ - - - . True
for
  trail :: 'st  $\Rightarrow$  ('v, unit, unit) marked-lits and
  clauses :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clNOT remove-clNOT:: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  propagate-conds :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  bool and
  inv :: 'st  $\Rightarrow$  bool
begin
lemma backjump-bj-can-jump:
  assumes
    tr-S: trail S = F' @ Marked K () # F and
    C: C  $\in$  # clauses S and
    tr-S-C: trail S  $\models_{\text{as}}$  CNot C and
    undef: undefined-lit F L and
    atm-L: atm-of L  $\in$  atms-of-msu (clauses S)  $\cup$  atm-of ' (lits-of (F' @ Marked K () # F)) and
    cls-S-C': clauses S  $\models_{\text{pm}}$  C' + {#L#} and
    F-C': F  $\models_{\text{as}}$  CNot C'
  shows  $\neg$ no-step backjump S
  using backjump.intros[OF tr-S - C tr-S-C undef - cls-S-C' F-C',
    of prepend-trail (Propagated L -) (reduce-trail-toNOT F S)] atm-L unfolding tr-S
  by (auto simp: state-eqNOT-def simp del: state-simpNOT)

sublocale dpll-with-backjumping-ops - - - - - inv  $\lambda$ - - - . True
  using backjump-bj-can-jump by unfold-locales auto
end

```

The restart does only reset the trail, contrary to Weidenbach's version. But there is a forget rule.

```

locale cdclNOT-merge-bj-learn-with-backtrack-restarts =
  cdclNOT-merge-bj-learn trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
  propagate-conds inv forget-conds
   $\lambda C L S$ . distinct-mset (C + {#L#})  $\wedge$  backjump-l-cond C L S
for

```

```

trail :: 'st  $\Rightarrow$  ('v::linorder, unit, unit) marked-lits and
clauses :: 'st  $\Rightarrow$  'v::linorder clauses and
prepend-trail :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
tl-trail :: 'st  $\Rightarrow$  'st and
add-clNOT remove-clNOT:: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
propagate-conds :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  bool and
inv :: 'st  $\Rightarrow$  bool and
forget-conds :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool and
backjump-l-cond :: 'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  bool
+
fixes f :: nat  $\Rightarrow$  nat
assumes
  unbounded: unbounded f and f-ge-1:  $\bigwedge n. n \geq 1 \Rightarrow f\ n \geq 1$  and
  inv-restart:  $\bigwedge S\ T. inv\ S \Rightarrow T \sim reduce\_trail\_to_{NOT} \ \square\ S \Rightarrow inv\ T$ 
begin

```

interpretation cdcl_{NOT}:

```

conflict-driven-clause-learning-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
propagate-conds inv backjump-conds ( $\lambda C. distinct\_mset\ C \wedge \neg tautology\ C$ ) forget-conds
by unfold-locales

```

interpretation cdcl_{NOT}:

```

conflict-driven-clause-learning trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
propagate-conds inv backjump-conds ( $\lambda C. distinct\_mset\ C \wedge \neg tautology\ C$ ) forget-conds
apply unfold-locales
using cdclNOT-merged-bj-learn-forgetNOT cdcl-merged-inv learn-inv
by (auto simp add: cdclNOT.simps dpll-bj-inv)

```

definition not-simplified-cl_s A = {#C \in # A. tautology C $\vee \neg distinct_mset\ C$ #}

lemma build-all-simple-clss-or-not-simplified-cl_s:

```

assumes atms-of-msu (clauses S)  $\subseteq$  atms-of-ms A and
  x  $\in$  # clauses S and finite A
shows x  $\in$  build-all-simple-clss (atms-of-ms A)  $\vee$  x  $\in$  # not-simplified-cls (clauses S)

```

proof –

consider

```

  (simpl)  $\neg tautology\ x$  and distinct-mset x
| (n-simp) tautology x  $\vee \neg distinct\_mset\ x$ 
by auto

```

then show ?thesis

proof cases

case simpl

then have x \in build-all-simple-clss (atms-of-ms A)

```

  by (meson assms atms-of-atms-of-ms-mono atms-of-ms-finite build-all-simple-clss-mono
    distinct-mset-not-tautology-implies-in-build-all-simple-clss finite-subset
    mem-set-mset-iff subsetCE)

```

then show ?thesis **by** blast

next

case n-simp

then have x \in # not-simplified-cl_s (clauses S)

using ⟨x \in # clauses S⟩ **unfolding** not-simplified-cl_s-def **by** auto

then show ?thesis **by** blast

qed

qed

lemma *cdcl_{NOT}-merged-bj-learn-clauses-bound*:

assumes

cdcl_{NOT}-merged-bj-learn *S T* **and**

inv: *inv S* **and**

atms-clss: *atms-of-msu* (*clauses S*) \subseteq *atms-of-ms* *A* **and**

atms-trail: *atm-of* ‘(*lits-of* (*trail S*)) \subseteq *atms-of-ms* *A* **and**

n-d: *no-dup* (*trail S*) **and**

fin-A[*simp*]: *finite A*

shows *set-mset* (*clauses T*) \subseteq *set-mset* (*not-simplified-cls* (*clauses S*))

\cup *build-all-simple-clss* (*atms-of-ms A*)

using *assms*

proof (*induction rule*: *cdcl_{NOT}-merged-bj-learn.induct*)

case *cdcl_{NOT}-merged-bj-learn-decide_{NOT}*

then show ?*case* **using** *dpll-bj-clauses* **by** (*force dest*!: *build-all-simple-clss-or-not-simplified-cls*)

next

case *cdcl_{NOT}-merged-bj-learn-propagate_{NOT}*

then show ?*case* **using** *dpll-bj-clauses* **by** (*force dest*!: *build-all-simple-clss-or-not-simplified-cls*)

next

case *cdcl_{NOT}-merged-bj-learn-forget_{NOT}*

then show ?*case* **using** *clauses-remove-cl_{NOT}* **unfolding** *state-eq_{NOT}-def*

by (*force elim*!: *forgetE* *dest*: *build-all-simple-clss-or-not-simplified-cls*)

next

case (*cdcl_{NOT}-merged-bj-learn-backjump-l T*) **note** *bj* = *this*(1) **and** *inv* = *this*(2) **and**

atms-clss = *this*(3) **and** *atms-trail* = *this*(4) **and** *n-d* = *this*(5)

have *cdcl_{NOT}** S T*

apply (*rule rtranclp-cdcl_{NOT}-merged-bj-learn-is-rtranclp-cdcl_{NOT}*)

using ‘*backjump-l S T*’ *inv* *cdcl_{NOT}-merged-bj-learn.simps* *n-d* **by** *blast+*

have *atm-of* ‘(*lits-of* (*trail T*)) \subseteq *atms-of-ms A*

using *cdcl_{NOT}.rtranclp-cdcl_{NOT}-trail-clauses-bound*[*OF* ‘*cdcl_{NOT}** S T*’] *inv* *atms-trail* *atms-clss* *n-d* **by** *auto*

have *atms-of-msu* (*clauses T*) \subseteq *atms-of-ms A*

using *cdcl_{NOT}.rtranclp-cdcl_{NOT}-trail-clauses-bound*[*OF* ‘*cdcl_{NOT}** S T*’] *inv* *n-d* *atms-clss* *atms-trail* **by** *fast*

moreover have *no-dup* (*trail T*)

using *cdcl_{NOT}.rtranclp-cdcl_{NOT}-no-dup*[*OF* ‘*cdcl_{NOT}** S T*’] *inv* *n-d* **by** *fast*

obtain *F' K F L l C' C* **where**

tr-S: *trail S* = *F' @ Marked K* () # *F* **and**

T: *T* \sim *prepend-trail* (*Propagated L l*) (*reduce-trail-to_{NOT}* *F* (*add-cl_{NOT}* (*C' + {#L#}*) *S*)) **and**

C \in # *clauses S* **and**

trail S \models_{as} *CNot C* **and**

undef: *undefined-lit F L* **and**

atm-of L = *atm-of K* \vee *atm-of L* \in *atms-of-msu* (*clauses S*)

\vee *atm-of L* \in *atm-of* ‘(*lits-of F'* \cup *lits-of F*)’ **and**

clauses S \models_{pm} *C' + {#L#}* **and**

F \models_{as} *CNot C'* **and**

dist: *distinct-mset* (*C' + {#L#}*) **and**

tauto: \neg *tautology* (*C' + {#L#}*) **and**

backjump-l-cond C' L T

using ‘*backjump-l S T*’ **apply** (*induction rule*: *backjump-l.induct*) **by** *auto*

have *atms-of C'* \subseteq *atm-of* ‘(*lits-of F*)’

```

using  $\langle F \models_{as} C \text{Not } C' \rangle$  by (simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
  atms-of-def image-subset-iff in-CNot-implies-uminus(2))
then have atms-of ( $C' + \{\#L\# \}$ )  $\subseteq$  atms-of-ms A
  using T  $\langle \text{atm-of } \text{'lits-of'} (\text{trail } T) \subseteq \text{atms-of-ms } A \rangle$  tr-S undef n-d by auto
then have build-all-simple-clss (atms-of ( $C' + \{\#L\# \}$ ))  $\subseteq$  build-all-simple-clss (atms-of-ms A)
  apply – by (rule build-all-simple-clss-mono) (simp-all)
then have  $C' + \{\#L\# \} \in \text{build-all-simple-clss } (\text{atms-of-ms } A)$ 
  using distinct-mset-not-tautology-implies-in-build-all-simple-clss[OF dist tauto]
  by auto
then show ?case
  using T inv atms-clss undef tr-S n-d
  by (force dest!: build-all-simple-clss-or-not-simplified-clss)
qed

```

lemma *cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*:

```

assumes cdclNOT-merged-bj-learn S T
shows (not-simplified-clss (clauses T))  $\subseteq \#$  (not-simplified-clss (clauses S))
using assms apply induction
prefer 4
unfolding not-simplified-clss-def apply (auto elim!: backjump-lE forgetE)[3]
by (elim backjump-lE) auto

```

lemma *rtranclp-cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*:

```

assumes cdclNOT-merged-bj-learn** S T
shows (not-simplified-clss (clauses T))  $\subseteq \#$  (not-simplified-clss (clauses S))
using assms apply induction
  apply simp
by (drule cdclNOT-merged-bj-learn-not-simplified-decreasing) auto

```

lemma *rtranclp-cdcl_{NOT}-merged-bj-learn-clauses-bound*:

```

assumes
  cdclNOT-merged-bj-learn** S T and
  inv S and
  atms-of-msu (clauses S)  $\subseteq$  atms-of-ms A and
  atm-of  $\langle \text{'lits-of'} (\text{trail } S) \rangle \subseteq$  atms-of-ms A and
  n-d: no-dup (trail S) and
  finite[simp]: finite A
shows set-mset (clauses T)  $\subseteq$  set-mset (not-simplified-clss (clauses S))
   $\cup$  build-all-simple-clss (atms-of-ms A)
using assms(1-5)
proof induction
  case base
  then show ?case by (auto dest!: build-all-simple-clss-or-not-simplified-clss)
next
  case (step T U) note st = this(1) and cdclNOT = this(2) and IH = this(3)[OF this(4-7)] and
    inv = this(4) and atms-clss-S = this(5) and atms-trail-S = this(6) and finite-clss-S = this(7)
  have st': cdclNOT** S T
    using inv rtranclp-cdclNOT-merged-bj-learn-is-rtranclp-cdclNOT-and-inv st n-d by blast
  have inv T
    using inv rtranclp-cdclNOT-merged-bj-learn-inv st n-d by blast
moreover
  have atms-of-msu (clauses T)  $\subseteq$  atms-of-ms A and
    atm-of  $\langle \text{'lits-of'} (\text{trail } T) \rangle \subseteq$  atms-of-ms A
    using cdclNOT.rtranclp-cdclNOT-trail-clauses-bound[OF st'] inv atms-clss-S atms-trail-S n-d
    by blast+

```

moreover moreover have *no-dup* (*trail T*)
using *cdcl_{NOT}.rtrancp-cdcl_{NOT}-no-dup*[*OF* $\langle \text{cdcl}_{NOT}^{**} S T \rangle \text{ inv } n\text{-d}$] **by** *fast*
ultimately have *set-mset* (*clauses U*)
 $\subseteq \text{set-mset } (\text{not-simplified-cls } (\text{clauses } T)) \cup \text{build-all-simple-clss } (\text{atms-of-ms } A)$
using *cdcl_{NOT} finite cdcl_{NOT}-merged-bj-learn-clauses-bound*
by (*auto intro!*: *cdcl_{NOT}-merged-bj-learn-clauses-bound*)
moreover have *set-mset* (*not-simplified-cls* (*clauses T*))
 $\subseteq \text{set-mset } (\text{not-simplified-cls } (\text{clauses } S))$
using *rtrancp-cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*[*OF st*] **by** *auto*
ultimately show *?case using IH inv atms-clss-S*
by (*auto dest!*: *build-all-simple-clss-or-not-simplified-cls*)
qed

abbreviation $\mu_{CDCL}'\text{-bound}$ **where**
 $\mu_{CDCL}'\text{-bound } A \ T == ((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))) * 2$
 $+ \text{card } (\text{set-mset } (\text{not-simplified-cls}(\text{clauses } T)))$
 $+ 3 \wedge \text{card } (\text{atms-of-ms } A)$

lemma *rtrancp-cdcl_{NOT}-merged-bj-learn-clauses-bound-card*:

assumes
*cdcl_{NOT}-merged-bj-learn^{**} S T and*
inv S and
atms-of-msu (clauses S) \subseteq atms-of-ms A and
atm-of ' (lits-of (trail S)) \subseteq atms-of-ms A and
n-d: no-dup (trail S) and
finite: finite A
shows $\mu_{CDCL}'\text{-merged } A \ T \leq \mu_{CDCL}'\text{-bound } A \ S$
proof –
have *set-mset* (*clauses T*) $\subseteq \text{set-mset } (\text{not-simplified-cls}(\text{clauses } S))$
 $\cup \text{build-all-simple-clss } (\text{atms-of-ms } A)$
using *rtrancp-cdcl_{NOT}-merged-bj-learn-clauses-bound*[*OF assms*] .
moreover have *card* (*set-mset* (*not-simplified-cls*(*clauses S*)))
 $\cup \text{build-all-simple-clss } (\text{atms-of-ms } A))$
 $\leq \text{card } (\text{set-mset } (\text{not-simplified-cls}(\text{clauses } S))) + 3 \wedge \text{card } (\text{atms-of-ms } A)$
by (*meson Nat.le-trans atms-of-ms-finite build-all-simple-clss-card card-Un-le finite*
nat-add-left-cancel-le)
ultimately have *card* (*set-mset* (*clauses T*)))
 $\leq \text{card } (\text{set-mset } (\text{not-simplified-cls}(\text{clauses } S))) + 3 \wedge \text{card } (\text{atms-of-ms } A)$
by (*meson build-all-simple-clss-finite card-mono dual-order.trans finite-UnI finite-set-mset*)
moreover have $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A \ T) * 2$
 $\leq (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) * 2$
by *auto*
ultimately show *?thesis unfolding $\mu_{CDCL}'\text{-merged-def}$ by auto*
qed

sublocale *cdcl_{NOT}-increasing-restarts-ops* $\lambda S \ T. \ T \sim \text{reduce-trail-to}_{NOT} \ \Box \ S$

cdcl_{NOT}-merged-bj-learn f
 $\lambda A \ S. \text{atms-of-msu } (\text{clauses } S) \subseteq \text{atms-of-ms } A$
 $\wedge \text{atm-of ' lits-of } (\text{trail } S) \subseteq \text{atms-of-ms } A \wedge \text{finite } A$
 $\mu_{CDCL}'\text{-merged}$
 $\lambda S. \text{inv } S \wedge \text{no-dup } (\text{trail } S)$
 $\mu_{CDCL}'\text{-bound}$
apply *unfold-locales*

using *unbounded apply simp*
using *f-ge-1 apply force*


```

    apply (blast dest!: cdclNOT-merged-bj-learn-is-tranclp-cdclNOT tranclp-into-rtranclp
      cdclNOT.rtranclp-cdclNOT-trail-clauses-bound )
    apply (simp add: cdclNOT-decreasing-measure^)
    using rtranclp-cdclNOT-merged-bj-learn-clauses-bound-card apply blast
    apply (drule rtranclp-cdclNOT-merged-bj-learn-not-simplified-decreasing)
    apply (auto dest!: simp: card-mono set-mset-mono )[]
  apply simp
  apply auto[]
  using cdclNOT-merged-bj-learn-no-dup-inv cdcl-merged-inv apply blast
  apply (auto simp: inv-restart)[]
done

```

lemma $cdcl_{NOT}\text{-restart-}\mu_{CDCL}'\text{-merged-le-}\mu_{CDCL}'\text{-bound}$:

```

assumes
  cdclNOT-restart  $T\ V$ 
  inv (fst  $T$ ) and
  no-dup (trail (fst  $T$ )) and
  atms-of-msu (clauses (fst  $T$ ))  $\subseteq$  atms-of-ms  $A$  and
  atm-of ' lits-of (trail (fst  $T$ ))  $\subseteq$  atms-of-ms  $A$  and
  finite  $A$ 
shows  $\mu_{CDCL}'\text{-merged } A\ (fst\ V) \leq \mu_{CDCL}'\text{-bound } A\ (fst\ T)$ 
using assms
proof induction
  case (restart-full  $S\ T\ n$ )
  show ?case
    unfolding fst-conv
    apply (rule rtranclp-cdclNOT-merged-bj-learn-clauses-bound-card)
    using restart-full unfolding full1-def by (force dest!: tranclp-into-rtranclp)+
next
  case (restart-step  $m\ S\ T\ n\ U$ ) note st = this(1) and  $U = this(3)$  and inv = this(4) and
    n-d = this(5) and atms-clss = this(6) and atms-trail = this(7) and finite = this(8)
  then have st':  $cdcl_{NOT}\text{-merged-bj-learn}^{**}\ S\ T$ 
    by (blast dest: relpowp-imp-rtranclp)
  then have st'':  $cdcl_{NOT}^{**}\ S\ T$ 
    using inv n-d apply - by (rule rtranclp-cdclNOT-merged-bj-learn-is-rtranclp-cdclNOT) auto
  have inv  $T$ 
    apply (rule rtranclp-cdclNOT-merged-bj-learn-inv)
    using inv st' n-d by auto
  then have inv  $U$ 
    using  $U$  by (auto simp: inv-restart)
  have atms-of-msu (clauses  $T$ )  $\subseteq$  atms-of-ms  $A$ 
    using cdclNOT.rtranclp-cdclNOT-trail-clauses-bound[OF st'] inv atms-clss atms-trail n-d
    by simp
  then have atms-of-msu (clauses  $U$ )  $\subseteq$  atms-of-ms  $A$ 
    using  $U$  by simp
  have not-simplified-cls (clauses  $U$ )  $\subseteq\#$  not-simplified-cls (clauses  $T$ )
    using  $\langle U \sim \text{reduce-trail-to}_{NOT} \ \square\ T \rangle$  by auto
  moreover have not-simplified-cls (clauses  $T$ )  $\subseteq\#$  not-simplified-cls (clauses  $S$ )
    apply (rule rtranclp-cdclNOT-merged-bj-learn-not-simplified-decreasing)
    using  $\langle (cdcl_{NOT}\text{-merged-bj-learn} \sim m)\ S\ T \rangle$  by (auto dest!: relpowp-imp-rtranclp)
  ultimately have  $U\text{-S: not-simplified-cls (clauses } U) \subseteq\# \text{ not-simplified-cls (clauses } S)$ 
    by auto

```

```

have (set-mset (clauses  $U$ ))
   $\subseteq$  set-mset (not-simplified-cls (clauses  $U$ ))  $\cup$  build-all-simple-clss (atms-of-ms  $A$ )

```

```

apply (rule rtrancp-cdclNOT-merged-bj-learn-clauses-bound)
  apply simp
  using ⟨inv U⟩ apply simp
  using ⟨atms-of-msu (clauses U) ⊆ atms-of-ms A⟩ apply simp
  using U apply simp
  using U apply simp
  using finite apply simp
done
then have f1: card (set-mset (clauses U)) ≤ card (set-mset (not-simplified-cls (clauses U))
  ∪ build-all-simple-clss (atms-of-ms A))
by (meson build-all-simple-clss-finite card-mono finite-UnI finite-set-mset)

moreover have set-mset (not-simplified-cls (clauses U)) ∪ build-all-simple-clss (atms-of-ms A)
  ⊆ set-mset (not-simplified-cls (clauses S)) ∪ build-all-simple-clss (atms-of-ms A)
using U-S by auto
then have f2:
  card (set-mset (not-simplified-cls (clauses U)) ∪ build-all-simple-clss (atms-of-ms A))
    ≤ card (set-mset (not-simplified-cls (clauses S)) ∪ build-all-simple-clss (atms-of-ms A))
by (meson build-all-simple-clss-finite card-mono finite-UnI finite-set-mset)

moreover have card (set-mset (not-simplified-cls (clauses S))
  ∪ build-all-simple-clss (atms-of-ms A))
  ≤ card (set-mset (not-simplified-cls (clauses S))) + card (build-all-simple-clss (atms-of-ms A))
using card-Un-le by blast
moreover have card (build-all-simple-clss (atms-of-ms A)) ≤ 3 ^ card (atms-of-ms A)
using atms-of-ms-finite build-all-simple-clss-card local.finite by blast
ultimately have card (set-mset (clauses U))
  ≤ card (set-mset (not-simplified-cls (clauses S))) + 3 ^ card (atms-of-ms A)
by linarith
then show ?case unfolding μCDCL'-merged-def by auto
qed

lemma cdclNOT-restart-μCDCL'-bound-le-μCDCL'-bound:
assumes
  cdclNOT-restart T V and
  no-dup (trail (fst T)) and
  inv (fst T) and
  fin: finite A
shows μCDCL'-bound A (fst V) ≤ μCDCL'-bound A (fst T)
using assms(1-3)
proof induction
case (restart-full S T n)
have not-simplified-cls (clauses T) ⊆# not-simplified-cls (clauses S)
apply (rule rtrancp-cdclNOT-merged-bj-learn-not-simplified-decreasing)
using ⟨full1 cdclNOT-merged-bj-learn S T⟩ unfolding full1-def
by (auto dest: trancp-into-rtrancp)
then show ?case by (auto simp: card-mono set-mset-mono)
next
case (restart-step m S T n U) note st = this(1) and U = this(3) and n-d = this(4) and inv =
this(5)
then have st': cdclNOT-merged-bj-learn** S T
by (blast dest: relpowp-imp-rtrancp)
then have st'': cdclNOT** S T
using inv n-d apply - by (rule rtrancp-cdclNOT-merged-bj-learn-is-rtrancp-cdclNOT) auto
have inv T

```

apply (*rule rtranclp-cdcl_{NOT}-merged-bj-learn-inv*)
using *inv st' n-d* **by** *auto*
then have *inv U*
using *U* **by** (*auto simp: inv-restart*)
have *not-simplified-cls (clauses U) $\subseteq\#$ not-simplified-cls (clauses T)*
using $\langle U \sim \text{reduce-trail-to}_{NOT} \sqcup T \rangle$ **by** *auto*
moreover have *not-simplified-cls (clauses T) $\subseteq\#$ not-simplified-cls (clauses S)*
apply (*rule rtranclp-cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*)
using $\langle (\text{cdcl}_{NOT}\text{-merged-bj-learn} \tilde{m}) S T \rangle$ **by** (*auto dest!: relpowp-imp-rtranclp*)
ultimately have *U-S: not-simplified-cls (clauses U) $\subseteq\#$ not-simplified-cls (clauses S)*
by *auto*
then show *?case* **by** (*auto simp: card-mono set-mset-mono*)
qed

sublocale *cdcl_{NOT}-increasing-restarts - - - - f $\lambda S T. T \sim \text{reduce-trail-to}_{NOT} \sqcup S$*
 $\lambda A S. \text{atms-of-msu (clauses S)} \subseteq \text{atms-of-ms } A$
 $\wedge \text{atm-of ' lits-of (trail S)} \subseteq \text{atms-of-ms } A \wedge \text{finite } A$
 $\mu_{CDCL}'\text{-merged } \text{cdcl}_{NOT}\text{-merged-bj-learn}$
 $\lambda S. \text{inv } S \wedge \text{no-dup (trail S)}$
 $\lambda A T. ((2 + \text{card (atms-of-ms } A)) \wedge (1 + \text{card (atms-of-ms } A))) * 2$
 $+ \text{card (set-mset (not-simplified-cls (clauses T)))}$
 $+ 3 \wedge \text{card (atms-of-ms } A)$
apply *unfold-locales*
using *cdcl_{NOT}-restart- μ_{CDCL}' -merged-le- μ_{CDCL}' -bound* **apply** *force*
using *cdcl_{NOT}-restart- μ_{CDCL}' -bound-le- μ_{CDCL}' -bound* **by** *fastforce*

lemma *cdcl_{NOT}-restart-eq-sat-iff:*

assumes
 $\text{cdcl}_{NOT}\text{-restart } S T$ **and**
 $\text{no-dup (trail (fst S))}$
 inv (fst S)
shows $I \models_{\text{sextm}} \text{clauses (fst S)} \longleftrightarrow I \models_{\text{sextm}} \text{clauses (fst T)}$
using *assms*
proof (*induction rule: cdcl_{NOT}-restart.induct*)
case (*restart-full S T n*)
then have *cdcl_{NOT}-merged-bj-learn** S T*
by (*simp add: tranclp-into-rtranclp full1-def*)
then show *?case*
using *cdcl_{NOT}.rtranclp-cdcl_{NOT}-bj-sat-ext-iff restart-full.prem(1,2)*
 $\text{rtranclp-cdcl}_{NOT}\text{-merged-bj-learn-is-rtranclp-cdcl}_{NOT}$ **by** *auto*
next
case (*restart-step m S T n U*)
then have *cdcl_{NOT}-merged-bj-learn** S T*
by (*auto simp: tranclp-into-rtranclp full1-def dest!: relpowp-imp-rtranclp*)
then have $I \models_{\text{sextm}} \text{clauses } S \longleftrightarrow I \models_{\text{sextm}} \text{clauses } T$
using *cdcl_{NOT}.rtranclp-cdcl_{NOT}-bj-sat-ext-iff restart-step.prem(1,2)*
 $\text{rtranclp-cdcl}_{NOT}\text{-merged-bj-learn-is-rtranclp-cdcl}_{NOT}$ **by** *auto*
moreover have $I \models_{\text{sextm}} \text{clauses } T \longleftrightarrow I \models_{\text{sextm}} \text{clauses } U$
using *restart-step.hyps(3)* **by** *auto*
ultimately show *?case* **by** *auto*
qed

lemma *rtranclp-cdcl_{NOT}-restart-eq-sat-iff:*

assumes

```

    cdclNOT-restart** S T and
    inv: inv (fst S) and n-d: no-dup(trail (fst S))
  shows  $I \models_{\text{sextm}} \text{clauses } (fst S) \longleftrightarrow I \models_{\text{sextm}} \text{clauses } (fst T)$ 
  using assms(1)
proof (induction rule: rtrancpl-induct)
  case base
  then show ?case by simp
next
  case (step T U) note st = this(1) and cdcl = this(2) and IH = this(3)
  have inv (fst T) and no-dup (trail (fst T))
    using rtrancpl-cdclNOT-with-restart-cdclNOT-inv using st inv n-d by blast+
  then have  $I \models_{\text{sextm}} \text{clauses } (fst T) \longleftrightarrow I \models_{\text{sextm}} \text{clauses } (fst U)$ 
    using cdclNOT-restart-eq-sat-iff cdcl by blast
  then show ?case using IH by blast
qed

lemma cdclNOT-restart-all-decomposition-implies-m:
  assumes
    cdclNOT-restart S T and
    inv: inv (fst S) and n-d: no-dup(trail (fst S)) and
    all-decomposition-implies-m (clauses (fst S))
      (get-all-marked-decomposition (trail (fst S)))
  shows all-decomposition-implies-m (clauses (fst T))
    (get-all-marked-decomposition (trail (fst T)))
  using assms
proof (induction)
  case (restart-full S T n) note full = this(1) and inv = this(2) and n-d = this(3) and
    decomp = this(4)
  have st: cdclNOT-merged-bj-learn** S T and
    n-s: no-step cdclNOT-merged-bj-learn T
    using full unfolding full1-def by (fast dest: trancpl-into-rtrancpl)+
  have st': cdclNOT** S T
    using inv rtrancpl-cdclNOT-merged-bj-learn-is-rtrancpl-cdclNOT-and-inv st n-d by auto
  have inv T
    using rtrancpl-cdclNOT-cdclNOT-inv[OF st] inv n-d by auto
  then show ?case
    using cdclNOT.rtrancpl-cdclNOT-all-decomposition-implies[OF - - n-d decomp] st' inv by auto
next
  case (restart-step m S T n U) note st = this(1) and U = this(3) and inv = this(4) and
    n-d = this(5) and decomp = this(6)
  show ?case using U by auto
qed

```

```

lemma rtrancpl-cdclNOT-restart-all-decomposition-implies-m:
  assumes
    cdclNOT-restart** S T and
    inv: inv (fst S) and n-d: no-dup(trail (fst S)) and
    decomp: all-decomposition-implies-m (clauses (fst S))
      (get-all-marked-decomposition (trail (fst S)))
  shows all-decomposition-implies-m (clauses (fst T))
    (get-all-marked-decomposition (trail (fst T)))
  using assms
proof (induction)
  case base
  then show ?case using decomp by simp

```

next
case (*step* T U) **note** $st = \text{this}(1)$ **and** $cdcl = \text{this}(2)$ **and** $IH = \text{this}(3)[OF \text{ this}(4-)]$ **and**
 $inv = \text{this}(4)$ **and** $n-d = \text{this}(5)$ **and** $decomp = \text{this}(6)$
have inv (*fst* T) **and** $no-dup$ (*trail* (*fst* T))
using $rtrancplp-cdcl_{NOT}\text{-with-restart-cdcl}_{NOT}\text{-inv}$ **using** st inv $n-d$ **by** $blast+$
then show $?case$
using $cdcl_{NOT}\text{-restart-all-decomposition-implies-m}[OF \text{ cdcl}]$ IH **by** $auto$
qed

lemma $full-cdcl_{NOT}\text{-restart-normal-form}$:
assumes
 $full$: $full\ cdcl_{NOT}\text{-restart } S\ T$ **and**
 inv : inv (*fst* S) **and** $n-d$: $no-dup$ (*trail* (*fst* S)) **and**
 $decomp$: $all\text{-decomposition-implies-m}$ (*clauses* (*fst* S))
(*get-all-marked-decomposition* (*trail* (*fst* S))) **and**
 $atms\text{-cls}$: $atms\text{-of-msu}$ (*clauses* (*fst* S)) $\subseteq atms\text{-of-ms } A$ **and**
 $atms\text{-trail}$: $atm\text{-of ' lits-of}$ (*trail* (*fst* S)) $\subseteq atms\text{-of-ms } A$ **and**
 fin : $finite\ A$
shows $unsatisfiable$ ($set\text{-mset}$ (*clauses* (*fst* S)))
 $\vee \text{ lits-of}$ (*trail* (*fst* T)) \models_{sextm} *clauses* (*fst* S) \wedge $satisfiable$ ($set\text{-mset}$ (*clauses* (*fst* S)))

proof –
have $inv\text{-}T$: inv (*fst* T) **and** $n-d\text{-}T$: $no-dup$ (*trail* (*fst* T))
using $rtrancplp-cdcl_{NOT}\text{-with-restart-cdcl}_{NOT}\text{-inv}$ **using** $full\ inv\ n-d$ **unfolding** $full\text{-def}$ **by** $blast+$
moreover have
 $atms\text{-cls}\text{-}T$: $atms\text{-of-msu}$ (*clauses* (*fst* T)) $\subseteq atms\text{-of-ms } A$ **and**
 $atms\text{-trail}\text{-}T$: $atm\text{-of ' lits-of}$ (*trail* (*fst* T)) $\subseteq atms\text{-of-ms } A$
using $rtrancplp-cdcl_{NOT}\text{-with-restart-bound-inv}[of\ S\ T\ A]$ $full\ atms\text{-cls}\ atms\text{-trail}\ fin\ inv\ n-d$
unfolding $full\text{-def}$ **by** $blast+$
ultimately have $no\text{-step}\ cdcl_{NOT}\text{-merged-bj-learn}$ (*fst* T)
apply –
apply ($rule\ no\text{-step-cdcl}_{NOT}\text{-restart-no-step-cdcl}_{NOT}[of\ -\ A]$)
using $full$ **unfolding** $full\text{-def}$ **apply** $simp$
apply $simp$
using fin **apply** $simp$
done
moreover have $all\text{-decomposition-implies-m}$ (*clauses* (*fst* T))
(*get-all-marked-decomposition* (*trail* (*fst* T)))
using $rtrancplp-cdcl_{NOT}\text{-restart-all-decomposition-implies-m}[of\ S\ T]$ $inv\ n-d\ decomp$
full unfolding $full\text{-def}$ **by** $auto$
ultimately have $unsatisfiable$ ($set\text{-mset}$ (*clauses* (*fst* T)))
 $\vee \text{ trail}$ (*fst* T) \models_{asm} *clauses* (*fst* T) \wedge $satisfiable$ ($set\text{-mset}$ (*clauses* (*fst* T)))
apply –
apply ($rule\ cdcl_{NOT}\text{-merged-bj-learn-final-state}$)
using $atms\text{-cls}\text{-}T\ atms\text{-trail}\text{-}T\ fin\ n-d\text{-}T\ fin\ inv\text{-}T$ **by** $blast+$
then consider
($unsat$) $unsatisfiable$ ($set\text{-mset}$ (*clauses* (*fst* T)))
| (sat) trail (*fst* T) \models_{asm} *clauses* (*fst* T) **and** $satisfiable$ ($set\text{-mset}$ (*clauses* (*fst* T)))
by $auto$
then show $unsatisfiable$ ($set\text{-mset}$ (*clauses* (*fst* S)))
 $\vee \text{ lits-of}$ (*trail* (*fst* T)) \models_{sextm} *clauses* (*fst* S) \wedge $satisfiable$ ($set\text{-mset}$ (*clauses* (*fst* S)))
proof cases
case $unsat$
then have $unsatisfiable$ ($set\text{-mset}$ (*clauses* (*fst* S)))
unfolding $satisfiable\text{-def}$ **apply** $auto$
using $rtrancplp-cdcl_{NOT}\text{-restart-eq-sat-iff}[of\ S\ T]$ $full\ inv\ n-d$

```

    consistent-true-clss-ext-satisfiable true-clss-imp-true-clss-ext
    unfolding satisfiable-def full-def by blast
  then show ?thesis by blast
next
case sat
then have lits-of (trail (fst T))  $\models_{\text{sextm}}$  clauses (fst T)
  using true-clss-imp-true-clss-ext by (auto simp: true-annots-true-clss)
then have lits-of (trail (fst T))  $\models_{\text{sextm}}$  clauses (fst S)
  using rtrancplp-cdclNOT-restart-eq-sat-iff[of S T] full inv n-d unfolding full-def by blast
moreover then have satisfiable (set-mset (clauses (fst S)))
  using consistent-true-clss-ext-satisfiable distinctconsistent-interp n-d-T by fast
ultimately show ?thesis by fast
qed
qed

```

corollary *full-cdcl_{NOT}-restart-normal-form-init-state:*
assumes
init-state: trail $S = []$ clauses $S = N$ **and**
full: full cdcl_{NOT}-restart ($S, 0$) T **and**
inv: inv S
shows unsatisfiable (set-mset N)
 \vee lits-of (trail (fst T)) \models_{sextm} $N \wedge$ satisfiable (set-mset N)
using full-cdcl_{NOT}-restart-normal-form[of ($S, 0$) T] *assms* **by** auto

end

end
theory DPLL-NOT
imports CDCL-NOT
begin

15 DPLL as an instance of NOT

15.1 DPLL with simple backtrack

locale *dppl-with-backtrack*

begin

inductive *backtrack* :: ('v, unit, unit) marked-lit list \times 'v clauses
 \Rightarrow ('v, unit, unit) marked-lit list \times 'v clauses \Rightarrow bool **where**
backtrack-split (fst S) = ($M', L \# M$) \Longrightarrow is-marked $L \Longrightarrow D \in \#$ snd S
 \Longrightarrow fst $S \models_{\text{as}}$ CNot $D \Longrightarrow$ backtrack S (Propagated ($-$ (lit-of L)) () $\# M$, snd S)

inductive-cases *backtrackE*[elim]: *backtrack* (M, N) (M', N')

lemma *backtrack-is-backjump:*

fixes $M M' ::$ ('v, unit, unit) marked-lit list

assumes

backtrack: *backtrack* (M, N) (M', N') **and**

no-dup: (*no-dup* \circ fst) (M, N) **and**

decomp: all-decomposition-implies-m N (*get-all-marked-decomposition* M)

shows

$\exists C F' K F L l C'.$

$M = F' @ \text{Marked } K () \# F \wedge$

$M' = \text{Propagated } L l \# F \wedge N = N' \wedge C \in \# N \wedge F' @ \text{Marked } K d \# F \models_{\text{as}}$ CNot $C \wedge$

undefined-lit $F L \wedge \text{atm-of } L \in \text{atms-of-msu } N \cup \text{atm-of ' lits-of } (F' @ \text{Marked } K d \# F) \wedge$

$N \models_{\text{pm}}$ $C' + \{\#L\# \} \wedge F \models_{\text{as}}$ CNot C'

proof –

let $?S = (M, N)$

let $?T = (M', N')$

obtain $F F' P L D$ **where**

$b\text{-sp}$: *backtrack-split* $M = (F', L \# F)$ **and**

is-marked L **and**

$D \in \# \text{ snd } ?S$ **and**

$M \models_{as} CNot D$ **and**

bt : *backtrack* $?S$ (*Propagated* $(- (lit\text{-of } L)) P \# F, N$) **and**

M' : $M' = \text{Propagated } (- (lit\text{-of } L)) P \# F$ **and**

$[simp]$: $N' = N$

using *backtrackE*[*OF backtrack*] **by** (*metis backtrack fstI sndI*)

let $?K = lit\text{-of } L$

let $?C = \text{image-mset lit-of } \{\#K \in \#mset M. \text{is-marked } K \wedge K \neq L\# \} :: 'v \text{ literal multiset}$

let $?C' = \text{set-mset (image-mset single } (?C + \{\#?K\# \}))$

obtain K **where** $L = \text{Marked } K ()$ **using** $\langle \text{is-marked } L \rangle$ **by** (*cases* L) *auto*

have $M: M = F' @ \text{Marked } K () \# F$

using $b\text{-sp}$ **by** (*metis L backtrack-split-list-eq fst-conv snd-conv*)

moreover have $F' @ \text{Marked } K () \# F \models_{as} CNot D$

using $\langle M \models_{as} CNot D \rangle$ **unfolding** M .

moreover have *undefined-lit* $F (-?K)$

using *no-dup* **unfolding** $M L$ **by** (*simp add: defined-lit-map*)

moreover have *atm-of* $(-K) \in \text{atms-of-msu } N \cup \text{atm-of ' lits-of } (F' @ \text{Marked } K d \# F)$

by *auto*

moreover

have *set-mset* $N \cup ?C' \models_{ps} \{\{\#\}\}$

proof –

have $A: \text{set-mset } N \cup ?C' \cup (\lambda a. \{\#lit\text{-of } a\# \}) ' \text{set } M =$

set-mset $N \cup (\lambda a. \{\#lit\text{-of } a\# \}) ' \text{set } M$

unfolding $M L$ **by** *auto*

have *set-mset* $N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$

$\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) ' \text{set } M$

using *all-decomposition-implies-propagated-lits-are-implied*[*OF decomp*] .

moreover have $C': ?C' = \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$

unfolding $M L$ **apply** *standard*

apply *force*

using *IntI* **by** *auto*

ultimately have $N\text{-}C\text{-}M: \text{set-mset } N \cup ?C' \models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) ' \text{set } M$

by *auto*

have *set-mset* $N \cup (\lambda L. \{\#lit\text{-of } L\# \}) ' (\text{set } M) \models_{ps} \{\{\#\}\}$

unfolding *true-clss-clss-def*

proof (*intro allI impI, goal-cases*)

case (1 I) **note** $tot = \text{this}(1)$ **and** $cons = \text{this}(2)$ **and** $I\text{-}N\text{-}M = \text{this}(3)$

have $I \models D$

using $I\text{-}N\text{-}M \langle D \in \# \text{ snd } ?S \rangle$ **unfolding** *true-clss-def* **by** *auto*

moreover have $I \models_s CNot D$

using $\langle M \models_{as} CNot D \rangle$ **unfolding** M **by** (*metis* 1(3) $\langle M \models_{as} CNot D \rangle$

true-annots-true-clss true-clss-mono-set-mset-l true-clss-def

true-clss-singleton-lit-of-implies-incl true-clss-union)

ultimately show $?case$ **using** *cons consistent-CNot-not* **by** *blast*

qed

then show $?thesis$

using *true-clss-clss-left-right*[*OF N-C-M, of* $\{\{\#\}\}$] **unfolding** A **by** *auto*

qed

```

have N  $\models_{pm}$  image-mset uminus ?C + {#- ?K#}
  unfolding true-clss-clss-def true-clss-clss-def total-over-m-def
  proof (intro allI impI)
    fix I
    assume
      tot: total-over-set I (atms-of-ms (set-mset N  $\cup$  {image-mset uminus ?C + {#- ?K#}})) and
      cons: consistent-interp I and
      I  $\models_{sm}$  N
    have (K  $\in$  I  $\wedge$   $\neg$ K  $\notin$  I)  $\vee$  ( $\neg$ K  $\in$  I  $\wedge$  K  $\notin$  I)
      using cons tot unfolding consistent-interp-def L by (cases K) auto
    have total-over-set I (atm-of 'lit-of ' (set M  $\cap$  {L. is-marked L  $\wedge$  L  $\neq$  Marked K d}))
      using tot by (auto simp add: L atms-of-uminus-lit-atm-of-lit-of)

  then have H:  $\bigwedge x.$ 
    lit-of x  $\notin$  I  $\implies$  x  $\in$  set M  $\implies$  is-marked x
     $\implies$  x  $\neq$  Marked K d  $\implies$   $\neg$ lit-of x  $\in$  I

  unfolding total-over-set-def atms-of-s-def
  proof -
    fix x :: ('v, unit, unit) marked-lit
    assume a1: x  $\in$  set M
    assume a2:  $\forall l \in$  atm-of 'lit-of ' (set M  $\cap$  {L. is-marked L  $\wedge$  L  $\neq$  Marked K d}).
      Pos l  $\in$  I  $\vee$  Neg l  $\in$  I
    assume a3: lit-of x  $\notin$  I
    assume a4: is-marked x
    assume a5: x  $\neq$  Marked K d
    have f6: Neg (atm-of (lit-of x)) =  $\neg$  Pos (atm-of (lit-of x))
      by simp
    have Pos (atm-of (lit-of x))  $\in$  I  $\vee$  Neg (atm-of (lit-of x))  $\in$  I
      using a5 a4 a2 a1 by blast
    then show  $\neg$  lit-of x  $\in$  I
      using f6 a3 by (metis (no-types) atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
        literal.sel(1))
    qed
  have  $\neg$ I  $\models_s$  ?C'
    using (set-mset N  $\cup$  ?C'  $\models_{ps}$  {{#}}) tot cons (I  $\models_{sm}$  N)
    unfolding true-clss-clss-def total-over-m-def
    by (simp add: atms-of-uminus-lit-atm-of-lit-of atms-of-ms-single-image-atm-of-lit-of)
  then show I  $\models$  image-mset uminus ?C + {#- lit-of L#}
    unfolding true-clss-def true-clss-def Bex-mset-def
    using (K  $\in$  I  $\wedge$   $\neg$ K  $\notin$  I)  $\vee$  ( $\neg$ K  $\in$  I  $\wedge$  K  $\notin$  I)
    unfolding L by (auto dest!: H)
  qed
moreover
  have set F'  $\cap$  {K. is-marked K  $\wedge$  K  $\neq$  L} = {}
    using backtrack-split-fst-not-marked[of - M] b-sp by auto
  then have F  $\models_{as}$  CNot (image-mset uminus ?C)
    unfolding M CNot-def true-annots-def by (auto simp add: L lits-of-def)
  ultimately show ?thesis
    using M' (D  $\in$  # snd ?S) L by force
qed

lemma backtrack-is-backjump':
  fixes M M' :: ('v, unit, unit) marked-lit list
  assumes

```


backtrack: *backtrack* S T **and**
no-dup: (*no-dup* \circ *fst*) S **and**
decomp: *all-decomposition-implies-m* (*snd* S) (*get-all-marked-decomposition* (*fst* S))
shows
 $\exists C F' K F L \text{ l } C'.$
 $\text{fst } S = F' @ \text{Marked } K () \# F \wedge$
 $T = (\text{Propagated } L \text{ l } \# F, \text{snd } S) \wedge C \in \# \text{snd } S \wedge \text{fst } S \models_{as} CNot C$
 $\wedge \text{undefined-lit } F L \wedge \text{atm-of } L \in \text{atms-of-msu} (\text{snd } S) \cup \text{atm-of ' lits-of } (\text{fst } S) \wedge$
 $\text{snd } S \models_{pm} C' + \{\#L\# \} \wedge F \models_{as} CNot C'$
apply (*cases* S , *cases* T)
using *backtrack-is-backjump*[*of* *fst* S *snd* S *fst* T *snd* T] *assms* **by** *fastforce*

sublocale *dpll-state* *fst* *snd* $\lambda L (M, N). (L \# M, N) \lambda (M, N). (tl M, N)$
 $\lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, \text{remove-mset } C N)$
by *unfold-locales auto*

sublocale *backjumping-ops* *fst* *snd* $\lambda L (M, N). (L \# M, N) \lambda (M, N). (tl M, N)$
 $\lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, \text{remove-mset } C N) \lambda - S T. \text{backtrack } S T$
by *unfold-locales*

lemma *backtrack-is-backjump''*:
fixes $M M' :: ('v, unit, unit) \text{ marked-lit list}$
assumes
backtrack: *backtrack* S T **and**
no-dup: (*no-dup* \circ *fst*) S **and**
decomp: *all-decomposition-implies-m* (*snd* S) (*get-all-marked-decomposition* (*fst* S))
shows *backjump* S T

proof –
obtain $C F' K F L \text{ l } C'$ **where**
1: *fst* $S = F' @ \text{Marked } K () \# F$ **and**
2: $T = (\text{Propagated } L \text{ l } \# F, \text{snd } S)$ **and**
3: $C \in \# \text{snd } S$ **and**
4: *fst* $S \models_{as} CNot C$ **and**
5: *undefined-lit* $F L$ **and**
6: *atm-of* $L \in \text{atms-of-msu} (\text{snd } S) \cup \text{atm-of ' lits-of } (\text{fst } S)$ **and**
7: $\text{snd } S \models_{pm} C' + \{\#L\# \}$ **and**
8: $F \models_{as} CNot C'$
using *backtrack-is-backjump'*[*OF* *assms*] **by** *blast*
show *?thesis*
using *backjump.intros*[*OF* 1 - 3 4 5 6 7 8] 2 *backtrack* 1 5
by (*auto simp: state-eq_{NOT}-def simp del: state-simp_{NOT}*)
qed

lemma *can-do-bt-step*:
assumes
 $M: \text{fst } S = F' @ \text{Marked } K d \# F$ **and**
 $C \in \# \text{snd } S$ **and**
 $C: \text{fst } S \models_{as} CNot C$
shows $\neg \text{no-step backtrack } S$

proof –
obtain $L G' G$ **where**
backtrack-split (*fst* S) = ($G', L \# G$)
unfolding M **by** (*induction* F' *rule: marked-lit-list-induct*) *auto*
moreover then have *is-marked* L
by (*metis backtrack-split-snd-hd-marked list.distinct*(1) *list.sel*(1) *snd-conv*)

ultimately show *?thesis*
 using *backtrack.intros[of S G' L G C] (C ∈# snd S) C unfolding M by auto*
 qed

end

sublocale *dpll-with-backtrack* \subseteq *dpll-with-backjumping-ops fst snd* $\lambda L (M, N). (L \# M, N)$
 $\lambda (M, N). (tl\ M, N) \lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, remove\ mset\ C\ N) \lambda - -. True$
 $\lambda (M, N). no\ dup\ M \wedge all\ decomposition\ implies\ m\ N (get\ all\ marked\ decomposition\ M)$
 $(\lambda - - S\ T. backtrack\ S\ T)$
by *unfold-locales (metis (mono-tags, lifting) dpll-with-backtrack.backtrack-is-backjump''*
dpll-with-backtrack.can-do-bt-step prod.case-eq-if comp-apply)

sublocale *dpll-with-backtrack* \subseteq *dpll-with-backjumping fst snd* $\lambda L (M, N). (L \# M, N)$
 $\lambda (M, N). (tl\ M, N) \lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, remove\ mset\ C\ N) \lambda - -. True$
 $\lambda (M, N). no\ dup\ M \wedge all\ decomposition\ implies\ m\ N (get\ all\ marked\ decomposition\ M)$
 $(\lambda - - S\ T. backtrack\ S\ T)$
apply *unfold-locales*
using *dpll-bj-no-dup dpll-bj-all-decomposition-implies-inv* **apply** *fastforce*
done

sublocale *dpll-with-backtrack* \subseteq *conflict-driven-clause-learning-ops*
fst snd $\lambda L (M, N). (L \# M, N)$
 $\lambda (M, N). (tl\ M, N) \lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, remove\ mset\ C\ N) \lambda - -. True$
 $\lambda (M, N). no\ dup\ M \wedge all\ decomposition\ implies\ m\ N (get\ all\ marked\ decomposition\ M)$
 $(\lambda - - S\ T. backtrack\ S\ T) \lambda - -. False \lambda - -. False$
by *unfold-locales*

sublocale *dpll-with-backtrack* \subseteq *conflict-driven-clause-learning*
fst snd $\lambda L (M, N). (L \# M, N)$
 $\lambda (M, N). (tl\ M, N) \lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, remove\ mset\ C\ N) \lambda - -. True$
 $\lambda (M, N). no\ dup\ M \wedge all\ decomposition\ implies\ m\ N (get\ all\ marked\ decomposition\ M)$
 $(\lambda - - S\ T. backtrack\ S\ T) \lambda - -. False \lambda - -. False$
apply *unfold-locales*
using *cdcl_{NOT}.simps dpll-bj-inv forgetE learnE* **by** *blast*

context *dpll-with-backtrack*
begin
lemma *wf-tranclp-dpll-initail-state:*
assumes *fin: finite A*
shows *wf {((M'::('v, unit, unit) marked-lits, N'::'v clauses), ([], N)) | M' N' N.*
dpll-bj⁺⁺ ([], N) (M', N') \wedge atms-of-msu N \subseteq atms-of-ms A}
using *wf-tranclp-dpll-bj[OF assms(1)]* **by** *(rule wf-subset) auto*

corollary *full-dpll-final-state-conclusive:*
fixes *M M' :: ('v, unit, unit) marked-lit list*
assumes
full: full dpll-bj ([], N) (M', N')
shows *unsatisfiable (set-mset N) \vee (M' \models_{asm} N \wedge satisfiable (set-mset N))*
using *assms full-dpll-backjump-final-state[of ([], N) (M', N') set-mset N]* **by** *auto*

corollary *full-dpll-normal-form-from-init-state:*
fixes *M M' :: ('v, unit, unit) marked-lit list*
assumes
full: full dpll-bj ([], N) (M', N')

```

shows  $M' \models_{asm} N \longleftrightarrow \text{satisfiable } (\text{set-mset } N)$ 
proof -
  have no-dup  $M'$ 
    using rtracp-dpll-bj-no-dup[of  $([], N)$   $(M', N')$ ]
    full unfolding full-def by auto
  then have  $M' \models_{asm} N \implies \text{satisfiable } (\text{set-mset } N)$ 
    using distinctconsistent-interp satisfiable-carac' true-annots-true-cls by blast
  then show ?thesis
    using full-dpll-final-state-conclusive[OF full] by auto
qed

```

```

lemma cdclNOT-is-dpll:
  cdclNOT  $S$   $T \longleftrightarrow$  dpll-bj  $S$   $T$ 
  by (auto simp: cdclNOT.simps learn.simps forgetNOT.simps)

```

Another proof of termination:

```

lemma wf {( $T, S$ ). dpll-bj  $S$   $T \wedge$  cdclNOT-NOT-all-inv  $A$   $S$ }
  unfolding cdclNOT-is-dpll[symmetric]
  by (rule wf-cdclNOT-no-learn-and-forget-infinite-chain)
  (auto simp: learn.simps forgetNOT.simps)
end

```

15.2 Adding restarts

```

locale dpll-withbacktrack-and-restarts =
  dpll-with-backtrack +
  fixes  $f :: \text{nat} \Rightarrow \text{nat}$ 
  assumes unbounded: unbounded  $f$  and  $f\text{-ge-1} : \bigwedge n. n \geq 1 \implies f\ n \geq 1$ 
begin
  sublocale cdclNOT-increasing-restarts fst snd  $\lambda L$  ( $M, N$ ). ( $L \# M, N$ )  $\lambda(M, N)$ . ( $tl\ M, N$ )
     $\lambda C$  ( $M, N$ ). ( $M, \{\#C\# \} + N$ )  $\lambda C$  ( $M, N$ ). ( $M, \text{remove-mset } C\ N$ )  $f\ \lambda(-, N)$   $S$ .  $S = ([], N)$ 
   $\lambda A$  ( $M, N$ ).  $\text{atms-of-msu } N \subseteq \text{atms-of-ms } A \wedge \text{atm-of } ' \text{ lits-of } M \subseteq \text{atms-of-ms } A \wedge \text{finite } A$ 
     $\wedge \text{all-decomposition-implies-m } N$  ( $\text{get-all-marked-decomposition } M$ )
   $\lambda A$   $T$ .  $(2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$ 
     $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } T)$  dpll-bj
   $\lambda(M, N)$ . no-dup  $M \wedge \text{all-decomposition-implies-m } N$  ( $\text{get-all-marked-decomposition } M$ )
   $\lambda A$  -.  $(2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$ 
  apply unfold-locales
    apply (rule unbounded)
    using  $f\text{-ge-1}$  apply fastforce
    apply (smt dpll-bj-all-decomposition-implies-inv dpll-bj-atms-in-trail-in-set
      dpll-bj-clauses dpll-bj-no-dup prod.case-eq-if)
    apply (rule dpll-bj-trail-mes-decreasing-prop; auto)
    apply (case-tac  $T$ , simp)
    apply (case-tac  $U$ , simp)
    using dpll-bj-clauses dpll-bj-all-decomposition-implies-inv dpll-bj-no-dup by fastforce+
end

end
theory DPLL-W
imports Main Partial-Clausal-Logic Partial-Annotated-Clausal-Logic List-More Wellfounded-More
  DPLL-NOT
begin

```

16 DPLL

16.1 Rules

type-synonym $'a \text{ dpll}_W\text{-marked-lit} = ('a, \text{unit}, \text{unit}) \text{ marked-lit}$
type-synonym $'a \text{ dpll}_W\text{-marked-lits} = ('a, \text{unit}, \text{unit}) \text{ marked-lits}$
type-synonym $'v \text{ dpll}_W\text{-state} = 'v \text{ dpll}_W\text{-marked-lits} \times 'v \text{ clauses}$

abbreviation $\text{trail} :: 'v \text{ dpll}_W\text{-state} \Rightarrow 'v \text{ dpll}_W\text{-marked-lits}$ **where**
 $\text{trail} \equiv \text{fst}$
abbreviation $\text{clauses} :: 'v \text{ dpll}_W\text{-state} \Rightarrow 'v \text{ clauses}$ **where**
 $\text{clauses} \equiv \text{snd}$

The definition of DPLL is given in figure 2.13 page 70 of CW.

inductive $\text{dpll}_W :: 'v \text{ dpll}_W\text{-state} \Rightarrow 'v \text{ dpll}_W\text{-state} \Rightarrow \text{bool}$ **where**
 $\text{propagate: } C + \{\#L\# \} \in \# \text{ clauses } S \Longrightarrow \text{trail } S \models_{\text{as}} C \text{Not } C \Longrightarrow \text{undefined-lit } (\text{trail } S) \ L$
 $\Longrightarrow \text{dpll}_W \ S \ (\text{Propagated } L \ () \ \# \ \text{trail } S, \text{ clauses } S) \mid$
 $\text{decided: } \text{undefined-lit } (\text{trail } S) \ L \Longrightarrow \text{atm-of } L \in \text{atms-of-msu } (\text{clauses } S)$
 $\Longrightarrow \text{dpll}_W \ S \ (\text{Marked } L \ () \ \# \ \text{trail } S, \text{ clauses } S) \mid$
 $\text{backtrack: } \text{backtrack-split } (\text{trail } S) = (M', L \# M) \Longrightarrow \text{is-marked } L \Longrightarrow D \in \# \text{ clauses } S$
 $\Longrightarrow \text{trail } S \models_{\text{as}} C \text{Not } D \Longrightarrow \text{dpll}_W \ S \ (\text{Propagated } (- \ (\text{lit-of } L)) \ () \ \# \ M, \text{ clauses } S)$

16.2 Invariants

lemma $\text{dpll}_W\text{-distinct-inv:}$

assumes $\text{dpll}_W \ S \ S'$
and $\text{no-dup } (\text{trail } S)$
shows $\text{no-dup } (\text{trail } S')$
using assms

proof ($\text{induct rule: } \text{dpll}_W.\text{induct}$)

case ($\text{decided } L \ S$)

then show $?case$ **using** $\text{defined-lit-map by force}$

next

case ($\text{propagate } C \ L \ S$)

then show $?case$ **using** $\text{defined-lit-map by force}$

next

case ($\text{backtrack } S \ M' \ L \ M \ D$) **note** $\text{extracted} = \text{this}(1)$ **and** $\text{no-dup} = \text{this}(5)$

show $?case$

using $\text{no-dup backtrack-split-list-eq[of trail } S, \text{ symmetric}]$ **unfolding** extracted by auto

qed

lemma $\text{dpll}_W\text{-consistent-interp-inv:}$

assumes $\text{dpll}_W \ S \ S'$

and $\text{consistent-interp } (\text{lits-of } (\text{trail } S))$

and $\text{no-dup } (\text{trail } S)$

shows $\text{consistent-interp } (\text{lits-of } (\text{trail } S'))$

using assms

proof ($\text{induct rule: } \text{dpll}_W.\text{induct}$)

case ($\text{backtrack } S \ M' \ L \ M \ D$) **note** $\text{extracted} = \text{this}(1)$ **and** $\text{marked} = \text{this}(2)$ **and** $D = \text{this}(4)$ **and**
 $\text{cons} = \text{this}(5)$ **and** $\text{no-dup} = \text{this}(6)$

have $\text{no-dup}' : \text{no-dup } M$

by ($\text{metis } (\text{no-types}) \text{backtrack-split-list-eq distinct.simps}(2) \text{distinct-append extracted}$
 $\text{list.simps}(9) \text{map-append no-dup snd-conv}$)

then have $\text{insert } (\text{lit-of } L) \ (\text{lits-of } M) \subseteq \text{lits-of } (\text{trail } S)$

using $\text{backtrack-split-list-eq[of trail } S, \text{ symmetric}]$ **unfolding** extracted by auto

then have $\text{cons: consistent-interp } (\text{insert } (\text{lit-of } L) \ (\text{lits-of } M))$

using *consistent-interp-subset* cons by blast
 moreover
 have *lit-of* $L \notin \text{ lits-of } M$
 using *no-dup backtrack-split-list-eq*[of trail S , *symmetric*] *extracted*
 unfolding *lits-of-def* by force
 moreover
 have *atm-of* $(\neg \text{ lit-of } L) \notin (\lambda m. \text{ atm-of } (\text{ lit-of } m)) \text{ ' set } M$
 using *no-dup backtrack-split-list-eq*[of trail S , *symmetric*] **unfolding** *extracted* by force
 then have $\neg \text{ lit-of } L \notin \text{ lits-of } M$
 unfolding *lits-of-def* by force
 ultimately show ?case by simp
 qed (auto intro: *consistent-add-undefined-lit-consistent*)

lemma *dpll_W-vars-in-snd-inv*:
 assumes *dpll_W* $S S'$
 and *atm-of* ' $(\text{ lits-of } (\text{ trail } S)) \subseteq \text{ atms-of-msu } (\text{ clauses } S)$
 shows *atm-of* ' $(\text{ lits-of } (\text{ trail } S')) \subseteq \text{ atms-of-msu } (\text{ clauses } S')$
 using *assms*
proof (*induct* rule: *dpll_W.induct*)
 case (*backtrack* $S M' L M D$)
 then have *atm-of* $(\text{ lit-of } L) \in \text{ atms-of-msu } (\text{ clauses } S)$
 using *backtrack-split-list-eq*[of trail S , *symmetric*] by auto
 moreover
 have *atm-of* ' $\text{ lits-of } (\text{ trail } S) \subseteq \text{ atms-of-msu } (\text{ clauses } S)$
 using *backtrack*(5) by simp
 then have $\bigwedge x. x \in \text{ set } M \implies \text{ atm-of } (\text{ lit-of } x) \in \text{ atms-of-msu } (\text{ clauses } S)$
 using *backtrack-split-list-eq*[*symmetric*, of trail S] *backtrack.hyps*(1)
 unfolding *lits-of-def* by auto
 ultimately show ?case by (auto simp : *lits-of-def*)
 qed (auto simp: *in-plus-implies-atm-of-on-atms-of-ms*)

lemma *atms-of-ms-lit-of-atms-of*: *atms-of-ms* $((\lambda a. \{\# \text{ lit-of } a \# \}) \text{ ' } c) = \text{ atm-of ' lit-of ' } c$
 unfolding *atms-of-ms-def* using *image-iff* by force

Lemma theorem 2.8.2 page 71 of CW

lemma *dpll_W-propagate-is-conclusion*:
 assumes *dpll_W* $S S'$
 and *all-decomposition-implies-m* (*clauses* S) (*get-all-marked-decomposition* (*trail* S))
 and *atm-of* ' $\text{ lits-of } (\text{ trail } S) \subseteq \text{ atms-of-msu } (\text{ clauses } S)$
 shows *all-decomposition-implies-m* (*clauses* S') (*get-all-marked-decomposition* (*trail* S'))
 using *assms*
proof (*induct* rule: *dpll_W.induct*)
 case (*decided* $L S$)
 then show ?case **unfolding** *all-decomposition-implies-def* by simp
 next
 case (*propagate* $C L S$) **note** $\text{ inS} = \text{ this}(1)$ **and** $\text{ cnot} = \text{ this}(2)$ **and** $\text{ IH} = \text{ this}(4)$ **and** $\text{ undef} = \text{ this}(3)$ **and** $\text{ atms-incl} = \text{ this}(5)$
 let $?I = \text{ set } (\text{ map } (\lambda a. \{\# \text{ lit-of } a \# \}) (\text{ trail } S)) \cup \text{ set-mset } (\text{ clauses } S)$
 have $?I \models_p C + \{\# L \# \}$ by (auto simp add: *inS*)
 moreover have $?I \models_{ps} \text{ CNot } C$ using *true-annots-true-clss-cl* *cnot* by *fastforce*
 ultimately have $?I \models_p \{\# L \# \}$ using *true-clss-cl* *plus-CNot*[of $?I C L$] *inS* by blast
 {
 assume *get-all-marked-decomposition* (*trail* S) = []
 then have ?case by blast
 }

```

moreover {
  assume  $n$ : get-all-marked-decomposition (trail  $S$ )  $\neq []$ 
  have  $1$ :  $\bigwedge a\ b. (a, b) \in \text{set } (\text{tl } (\text{get-all-marked-decomposition } (\text{trail } S)))$ 
     $\implies ((\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } a \cup \text{set-mset } (\text{clauses } S)) \models_{ps} (\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } b$ 
    using IH unfolding all-decomposition-implies-def by (fastforce simp add: list.set-sel(2)  $n$ )
  moreover have  $2$ :  $\bigwedge a\ c. \text{hd } (\text{get-all-marked-decomposition } (\text{trail } S)) = (a, c)$ 
     $\implies ((\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } a \cup \text{set-mset } (\text{clauses } S)) \models_{ps} ((\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } c)$ 
    by (metis IH all-decomposition-implies-cons-pair all-decomposition-implies-single list.collapse  $n$ )
  moreover have  $3$ :  $\bigwedge a\ c. \text{hd } (\text{get-all-marked-decomposition } (\text{trail } S)) = (a, c)$ 
     $\implies ((\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } a \cup \text{set-mset } (\text{clauses } S)) \models_p \{\# L \#\}$ 
  proof –
    fix  $a\ c$ 
    assume  $h$ :  $\text{hd } (\text{get-all-marked-decomposition } (\text{trail } S)) = (a, c)$ 
    have  $h'$ :  $\text{trail } S = c @ a$  using get-all-marked-decomposition-decomp  $h$  by blast
    have  $I$ :  $\text{set } (\text{map } (\lambda a. \{\# \text{lit-of } a \#\})\ a) \cup \text{set-mset } (\text{clauses } S)$ 
       $\cup (\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } c \models_{ps} \text{CNot } C$ 
      using  $\langle ?I \models_{ps} \text{CNot } C \rangle$  unfolding  $h'$  by (simp add: Un-commute Un-left-commute)
    have
       $\text{atms-of-ms } (\text{CNot } C) \subseteq \text{atms-of-ms } (\text{set } (\text{map } (\lambda a. \{\# \text{lit-of } a \#\})\ a) \cup \text{set-mset } (\text{clauses } S))$ 
      and
       $\text{atms-of-ms } ((\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } c) \subseteq \text{atms-of-ms } (\text{set } (\text{map } (\lambda a. \{\# \text{lit-of } a \#\})\ a) \cup \text{set-mset } (\text{clauses } S))$ 
      apply (metis CNot-plus Un-subset-iff atms-of-atms-of-ms-mono atms-of-ms-CNot-atms-of atms-of-ms-union inS mem-set-mset-iff sup.coboundedI2)
      using inS atms-of-atms-of-ms-mono atms-incl by (fastforce simp: h')

    then have  $(\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } a \cup \text{set-mset } (\text{clauses } S) \models_{ps} \text{CNot } C$ 
      using true-clss-clss-left-right[OF - I]  $h\ 2$  by auto
    then show  $(\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } a \cup \text{set-mset } (\text{clauses } S) \models_p \{\# L \#\}$ 
      by (metis (no-types) Un-insert-right inS insertI1 mk-disjoint-insert inS mem-set-mset-iff true-clss-clss-in true-clss-clss-plus-CNot)
    qed
  ultimately have  $?case$ 
    by (case-tac hd (get-all-marked-decomposition (trail S)))
    (auto simp add: all-decomposition-implies-def)
}
ultimately show  $?case$  by auto
next
case (backtrack  $S\ M'\ L\ M\ D$ ) note  $\text{extracted} = \text{this}(1)$  and  $\text{marked} = \text{this}(2)$  and  $D = \text{this}(3)$  and
 $\text{cnot} = \text{this}(4)$  and  $\text{cons} = \text{this}(4)$  and  $IH = \text{this}(5)$  and  $\text{atms-incl} = \text{this}(6)$ 
have  $S$ :  $\text{trail } S = M' @ L \# M$ 
  using backtrack-split-list-eq[of trail S] unfolding  $\text{extracted}$  by auto
have  $M'$ :  $\forall l \in \text{set } M'. \neg \text{is-marked } l$ 
  using  $\text{extracted}$  backtrack-split-fst-not-marked[of - trail S] by simp
have  $n$ : get-all-marked-decomposition (trail  $S$ )  $\neq []$  by auto
then have all-decomposition-implies-m (clauses  $S$ )  $((L \# M, M')$ 
   $\# \text{tl } (\text{get-all-marked-decomposition } (\text{trail } S)))$ 
  by (metis (no-types) IH extracted get-all-marked-decomposition-backtrack-split list.exhaust-sel)
then have  $1$ :  $(\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } (L \# M) \cup \text{set-mset } (\text{clauses } S) \models_{ps} (\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } M'$ 
by simp
moreover
have  $(\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } (L \# M) \cup (\lambda a. \{\# \text{lit-of } a \#\}) \text{ ' set } M' \models_{ps} \text{CNot } D$ 
by (metis (mono-tags, lifting) S Un-commute cons image-Un set-append)

```

```

    true-annots-true-clss-clss)
  then have 2: (λa. {#lit-of a#}) ‘ set (L # M) ∪ set-mset (clauses S) ∪ (λa. {#lit-of a#}) ‘ set
M'
    |=ps CNot D
  by (metis (no-types, lifting) Un-assoc Un-left-commute true-clss-clss-union-l-r)
ultimately
  have set (map (λa. {#lit-of a#}) (L # M)) ∪ set-mset (clauses S) |=ps CNot D
  using true-clss-clss-left-right by fastforce
  then have set (map (λa. {#lit-of a#}) (L # M)) ∪ set-mset (clauses S) |=p {#}
  by (metis (mono-tags, lifting) D Un-def mem-Collect-eq set-mset-def
    true-clss-clss-contradiction-true-clss-clss-false)
  then have IL: (λa. {#lit-of a#}) ‘ set M ∪ set-mset (clauses S) |=p {#-lit-of L#}
  using true-clss-clss-false-left-right by auto
show ?case unfolding S all-decomposition-implies-def
proof
  fix x P level
  assume x: x ∈ set (get-all-marked-decomposition
    (fst (Propagated (− lit-of L) P # M, clauses S)))
  let ?M' = Propagated (− lit-of L) P # M
  let ?hd = hd (get-all-marked-decomposition ?M')
  let ?tl = tl (get-all-marked-decomposition ?M')
  have x = ?hd ∨ x ∈ set ?tl
  using x
  by (cases get-all-marked-decomposition ?M')
    auto
  moreover {
    assume x': x ∈ set ?tl
    have L': Marked (lit-of L) () = L using marked by (case-tac L, auto)
    have x ∈ set (get-all-marked-decomposition (M' @ L # M))
    using x' get-all-marked-decomposition-except-last-choice-equal[of M' lit-of L P M]
    L' by (metis (no-types) M' list.set-sel(2) tl-Nil)
    then have case x of (Ls, seen) ⇒ (λa. {#lit-of a#}) ‘ set Ls ∪ set-mset (clauses S)
    |=ps (λa. {#lit-of a#}) ‘ set seen
    using marked IH by (case-tac L) (auto simp add: S all-decomposition-implies-def)
  }
  moreover {
    assume x': x = ?hd
    have tl: tl (get-all-marked-decomposition (M' @ L # M)) ≠ []
    proof −
      have f1: ∧ms. length (get-all-marked-decomposition (M' @ ms))
        = length (get-all-marked-decomposition ms)
      by (simp add: M' get-all-marked-decomposition-remove-unmarked-length)
      have Suc (length (get-all-marked-decomposition M)) ≠ Suc 0
      by blast
      then show ?thesis
      using f1 marked by (metis (no-types) get-all-marked-decomposition.simps(1) length-tl
        list.sel(3) list.size(3) marked-lit.collapse(1))
    qed
    obtain M0' M0 where
      L0: hd (tl (get-all-marked-decomposition (M' @ L # M))) = (M0, M0')
      by (cases hd (tl (get-all-marked-decomposition (M' @ L # M))))
    have x'': x = (M0, Propagated (−lit-of L) P # M0')
    unfolding x' using get-all-marked-decomposition-last-choice tl M' L0
    by (metis marked marked-lit.collapse(1))
    obtain l-get-all-marked-decomposition where

```

```

    get-all-marked-decomposition (trail S) = (L # M, M') # (M0, M0') #
    l-get-all-marked-decomposition
    using get-all-marked-decomposition-backtrack-split extracted by (metis (no-types) L0 S
    hd-Cons-tl n tl)
  then have M = M0' @ M0 using get-all-marked-decomposition-hd-hd by fastforce
  then have IL': (λa. {#lit-of a#}) ' set M0 ∪ set-mset (clauses S)
    ∪ (λa. {#lit-of a#}) ' set M0' ⊨ps {#{#- lit-of L#}}
    using IL by (simp add: Un-commute Un-left-commute image-Un)
  moreover have H: (λa. {#lit-of a#}) ' set M0 ∪ set-mset (clauses S)
    ⊨ps (λa. {#lit-of a#}) ' set M0'
    using IH x'' unfolding all-decomposition-implies-def by (metis (no-types, lifting) L0 S
    list.set-sel(1) list.set-sel(2) old.prod.case tl tl-Nil)
  ultimately have case x of (Ls, seen) ⇒ (λa. {#lit-of a#}) ' set Ls ∪ set-mset (clauses S)
    ⊨ps (λa. {#lit-of a#}) ' set seen
    using true-clss-clss-left-right unfolding x'' by auto
}
ultimately show case x of (Ls, seen) ⇒
  (λa. {#lit-of a#}) ' set Ls ∪ set-mset (snd (?M', clauses S))
  ⊨ps (λa. {#lit-of a#}) ' set seen
  unfolding snd-conv by blast
qed
qed

```

Lemma theorem 2.8.3 page 72 of CW

```

theorem dpllW-propagate-is-conclusion-of-decided:
  assumes dpllW S S'
  and all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S))
  and atm-of ' lits-of (trail S) ⊆ atms-of-msu (clauses S)
  shows set-mset (clauses S') ∪ {#{#lit-of L#} | L. is-marked L ∧ L ∈ set (trail S')}
    ⊨ps (λa. {#lit-of a#}) ' ⋃ (set ' snd ' set (get-all-marked-decomposition (trail S')))
  using all-decomposition-implies-trail-is-implied[OF dpllW-propagate-is-conclusion[OF assms]] .

```

Lemma theorem 2.8.4 page 72 of CW

```

lemma only-propagated-vars-unsat:
  assumes marked: ∀ x ∈ set M. ¬ is-marked x
  and DN: D ∈ N and D: M ⊨as CNot D
  and inv: all-decomposition-implies N (get-all-marked-decomposition M)
  and atm-incl: atm-of ' lits-of M ⊆ atms-of-ms N
  shows unsatisfiable N
proof (rule ccontr)
  assume ¬ unsatisfiable N
  then obtain I where
    I: I ⊨s N and
    cons: consistent-interp I and
    tot: total-over-m I N
  unfolding satisfiable-def by auto
  then have I-D: I ⊨ D
    using DN unfolding true-clss-def by auto

  have l0: {#{#lit-of L#} | L. is-marked L ∧ L ∈ set M} = {} using marked by auto
  have atms-of-ms (N ∪ (λa. {#lit-of a#}) ' set M) = atms-of-ms N
    using atm-incl unfolding atms-of-ms-def lits-of-def by auto

  then have total-over-m I (N ∪ (λa. {#lit-of a#}) ' (set M))
    using tot unfolding total-over-m-def by auto

```



```

then have  $I \models_s (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' (set } M)$ 
  using all-decomposition-implies-propagated-lits-are-implied[OF inv] cons I
  unfolding true-clss-clss-def l0 by auto
then have  $IM: I \models_s (\lambda a. \{\#lit\text{-of } a\# \}) \text{ ' set } M$  by auto
{
  fix  $K$ 
  assume  $K \in \# D$ 
  then have  $-K \in lits\text{-of } M$ 
    by (auto split: split-if-asm
      intro: allE[OF D[unfolded true-annots-def Ball-def], of  $\{\#-K\# \}$ ])
  then have  $-K \in I$  using  $IM$  true-clss-singleton-lit-of-implies-incl by fastforce
}
then have  $\neg I \models D$  using cons unfolding true-clss-def consistent-interp-def by auto
then show False using I-D by blast
qed

```

lemma *dpll_W-same-clauses*:

```

assumes dpllW S S'
shows clauses S = clauses S'
using assms by (induct rule: dpllW.induct, auto)

```

lemma *rtranclp-dpll_W-inv*:

```

assumes rtranclp dpllW S S'
and inv: all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S))
and atm-incl: atm-of ' lits-of (trail S)  $\subseteq$  atms-of-msu (clauses S)
and consistent-interp (lits-of (trail S))
and no-dup (trail S)
shows all-decomposition-implies-m (clauses S') (get-all-marked-decomposition (trail S'))
and atm-of ' lits-of (trail S')  $\subseteq$  atms-of-msu (clauses S')
and clauses S = clauses S'
and consistent-interp (lits-of (trail S'))
and no-dup (trail S')
using assms

```

proof (*induct rule: rtranclp-induct*)

case *base*

show

```

all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S)) and
atm-of ' lits-of (trail S)  $\subseteq$  atms-of-msu (clauses S) and
clauses S = clauses S and
consistent-interp (lits-of (trail S)) and
no-dup (trail S) using assms by auto

```

next

```

case (step S' S'') note dpllWStar = this(1) and IH = this(3,4,5,6,7) and
dpllW = this(2)

```

moreover

assume

```

inv: all-decomposition-implies-m (clauses S) (get-all-marked-decomposition (trail S)) and
atm-incl: atm-of ' lits-of (trail S)  $\subseteq$  atms-of-msu (clauses S) and
cons: consistent-interp (lits-of (trail S)) and
no-dup (trail S)

```

ultimately have *decomp: all-decomposition-implies-m (clauses S')*

```

(get-all-marked-decomposition (trail S')) and

```

```

atm-incl': atm-of ' lits-of (trail S')  $\subseteq$  atms-of-msu (clauses S') and

```

```

snd: clauses S = clauses S' and

```

```

cons': consistent-interp (lits-of (trail S')) and

```

no_dup' : no_dup (trail S') **by** *blast* +
show $clauses\ S = clauses\ S''$ **using** $dpll_W$ -same-clauses[*OF* $dpll_W$] *snd* **by** *metis*

show $all_decomposition_implies_m$ ($clauses\ S''$) ($get_all_marked_decomposition$ (trail S''))
using $dpll_W$ -propagate-is-conclusion[*OF* $dpll_W$] *decomp atm-incl'* **by** *auto*
show atm_of ' $lits_of$ (trail S'') \subseteq $atms_of_msu$ ($clauses\ S''$)
using $dpll_W$ -vars-in-snd-inv[*OF* $dpll_W$] *atm-incl atm-incl'* **by** *auto*
show no_dup (trail S'') **using** $dpll_W$ -distinct-inv[*OF* $dpll_W$] no_dup' $dpll_W$ **by** *auto*
show $consistent_interp$ ($lits_of$ (trail S''))
using $cons'$ no_dup' $dpll_W$ -consistent-interp-inv[*OF* $dpll_W$] **by** *auto*
qed

definition $dpll_W$ -all-inv $S \equiv$
 $(all_decomposition_implies_m$ ($clauses\ S$) ($get_all_marked_decomposition$ (trail S))
 \wedge atm_of ' $lits_of$ (trail S) \subseteq $atms_of_msu$ ($clauses\ S$)
 \wedge $consistent_interp$ ($lits_of$ (trail S))
 \wedge no_dup (trail S))

lemma $dpll_W$ -all-inv-dest[*dest*]:
assumes $dpll_W$ -all-inv S
shows $all_decomposition_implies_m$ ($clauses\ S$) ($get_all_marked_decomposition$ (trail S))
and atm_of ' $lits_of$ (trail S) \subseteq $atms_of_msu$ ($clauses\ S$)
and $consistent_interp$ ($lits_of$ (trail S)) \wedge no_dup (trail S)
using *assms* **unfolding** $dpll_W$ -all-inv-def *lits-of-def* **by** *auto*

lemma $rtranclp$ - $dpll_W$ -all-inv:
assumes $rtranclp$ $dpll_W$ $S\ S'$
and $dpll_W$ -all-inv S
shows $dpll_W$ -all-inv S'
using *assms* $rtranclp$ - $dpll_W$ -inv[*OF* *assms*(1)] **unfolding** $dpll_W$ -all-inv-def *lits-of-def* **by** *blast*

lemma $dpll_W$ -all-inv:
assumes $dpll_W$ $S\ S'$
and $dpll_W$ -all-inv S
shows $dpll_W$ -all-inv S'
using *assms* $rtranclp$ - $dpll_W$ -all-inv **by** *blast*

lemma $rtranclp$ - $dpll_W$ -inv-starting-from-0:
assumes $rtranclp$ $dpll_W$ $S\ S'$
and inv : trail $S = []$
shows $dpll_W$ -all-inv S'

proof –
have $dpll_W$ -all-inv S
using *assms* **unfolding** $all_decomposition_implies_def$ $dpll_W$ -all-inv-def **by** *auto*
then show ?thesis **using** $rtranclp$ - $dpll_W$ -all-inv[*OF* *assms*(1)] **by** *blast*
qed

lemma $dpll_W$ -can-do-step:
assumes $consistent_interp$ (set M)
and $distinct$ M
and atm_of ' (set M) \subseteq $atms_of_msu$ N
shows $rtranclp$ $dpll_W$ ($[], N$) (map ($\lambda M. Marked\ M\ ()$) M, N)
using *assms*
proof (*induct* M)
case *Nil*

```

then show ?case by auto
next
case (Cons L M)
then have undefined-lit (map (λM. Marked M ()) M) L
  unfolding defined-lit-def consistent-interp-def by auto
moreover have atm-of L ∈ atms-of-msu N using Cons.premis(3) by auto
ultimately have dpllW (map (λM. Marked M ()) M, N) (map (λM. Marked M ()) (L # M), N)
  using dpllW.decided by auto
moreover have consistent-interp (set M) and distinct M and atm-of ‘ set M ⊆ atms-of-msu N
  using Cons.premis unfolding consistent-interp-def by auto
ultimately show ?case using Cons.hyps by auto
qed

```

definition *conclusive-dpll_W-state* ($S :: 'v \text{ dpll}_W\text{-state}$) \longleftrightarrow
 $(\text{trail } S \models_{\text{asm}} \text{clauses } S \vee ((\forall L \in \text{set } (\text{trail } S)). \neg \text{is-marked } L)$
 $\wedge (\exists C \in \# \text{clauses } S. \text{trail } S \models_{\text{as}} \text{CNot } C)))$

lemma *dpll_W-strong-completeness*:

```

assumes set M ⊢sm N
and consistent-interp (set M)
and distinct M
and atm-of ‘ (set M) ⊆ atms-of-msu N
shows dpllW** ([], N) (map (λM. Marked M ()) M, N)
and conclusive-dpllW-state (map (λM. Marked M ()) M, N)
proof –
show rtranclp dpllW ([], N) (map (λM. Marked M ()) M, N) using dpllW-can-do-step assms by auto
have map (λM. Marked M ()) M ⊢asm N using assms(1) true-annots-marked-true-clis by auto
then show conclusive-dpllW-state (map (λM. Marked M ()) M, N)
  unfolding conclusive-dpllW-state-def by auto
qed

```

lemma *dpll_W-sound*:

```

assumes
  rtranclp dpllW ([], N) (M, N) and
  ∀ S. ¬dpllW (M, N) S
shows M ⊢asm N ⟷ satisfiable (set-mset N) (is ?A ⟷ ?B)
proof
let ?M' = lits-of M
assume ?A
then have ?M' ⊢sm N by (simp add: true-annots-true-clis)
moreover have consistent-interp ?M'
  using rtranclp-dpllW-inv-starting-from-0[OF assms(1)] by auto
ultimately show ?B by auto
next
assume ?B
show ?A
proof (rule ccontr)
assume n: ¬ ?A
have (∃ L. undefined-lit M L ∧ atm-of L ∈ atms-of-msu N) ∨ (∃ D ∈ #N. M ⊢as CNot D)
proof –
obtain D :: 'a clause where D: D ∈ # N and ¬ M ⊢a D
  using n unfolding true-annots-def Ball-def by auto
then have (∃ L. undefined-lit M L ∧ atm-of L ∈ atms-of D) ∨ M ⊢as CNot D

```

```

    unfolding true-annots-def Ball-def CNot-def true-annot-def
    using atm-of-lit-in-atms-of true-annot-iff-marked-or-true-lit true-cls-def by blast
  then show ?thesis

    using D apply auto by (meson atms-of-atms-of-ms-mono mem-set-mset-iff subset-eq)
  qed
  moreover {
    assume  $\exists L. \text{undefined-lit } M \ L \wedge \text{atm-of } L \in \text{atms-of-msu } N$ 
    then have False using assms(2) decided by fastforce
  }
  moreover {
    assume  $\exists D \in \#N. M \models_{as} CNot \ D$ 
    then obtain D where DN:  $D \in \# \ N$  and MD:  $M \models_{as} CNot \ D$  by auto
    {
      assume  $\forall l \in \text{set } M. \neg \text{is-marked } l$ 
      moreover have  $dpll_W\text{-all-inv } ([], N)$ 
      using assms unfolding all-decomposition-implies-def  $dpll_W\text{-all-inv-def}$  by auto
      ultimately have unsatisfiable (set-mset N)
      using only-propagated-vars-unsat[of M D set-mset N] DN MD
      rtranclp- $dpll_W\text{-all-inv}$ [OF assms(1)] by force
      then have False using  $\langle ?B \rangle$  by blast
    }
    moreover {
      assume  $l: \exists l \in \text{set } M. \text{is-marked } l$ 
      then have False
      using backtrack[of (M, N) - - - D] DN MD assms(2)
      backtrack-split-some-is-marked-then-snd-has-hd[OF l]
      by (metis backtrack-split-snd-hd-marked fst-conv list.distinct(1) list.sel(1) snd-conv)
    }
    ultimately have False by blast
  }
  ultimately show False by blast
  qed
qed

```

16.3 Termination

definition $dpll_W\text{-mes } M \ n =$

$\text{map } (\lambda l. \text{if is-marked } l \text{ then } 2 \text{ else } (1::\text{nat})) (\text{rev } M) \ @ \ \text{replicate } (n - \text{length } M) \ 3$

lemma $\text{length-}dpll_W\text{-mes}$:

assumes $\text{length } M \leq n$

shows $\text{length } (dpll_W\text{-mes } M \ n) = n$

using assms unfolding $dpll_W\text{-mes-def}$ by auto

lemma $\text{distinctcard-atm-of-lit-of-eq-length}$:

assumes $\text{no-dup } S$

shows $\text{card } (\text{atm-of } \text{' lits-of } S) = \text{length } S$

using assms by (induct S) (auto simp add: image-image lits-of-def)

lemma $dpll_W\text{-card-decrease}$:

assumes $dpll: dpll_W \ S \ S' \text{ and } \text{length } (\text{trail } S') \leq \text{card vars}$

and $\text{length } (\text{trail } S) \leq \text{card vars}$

shows $(dpll_W\text{-mes } (\text{trail } S') \ (\text{card vars}), dpll_W\text{-mes } (\text{trail } S) \ (\text{card vars}))$

$\in \text{lexn } \{(a, b). a < b\} \ (\text{card vars})$

using assms

```

proof (induct rule: dpllW.induct)
  case (propagate C L S)
  have m: map ( $\lambda l. \text{if is-marked } l \text{ then } 2 \text{ else } 1$ ) (rev (trail S))
    @ replicate (card vars – length (trail S)) 3
  = map ( $\lambda l. \text{if is-marked } l \text{ then } 2 \text{ else } 1$ ) (rev (trail S)) @ 3
    # replicate (card vars – Suc (length (trail S))) 3
  using propagate.premis[simplified] using Suc-diff-le by fastforce
  then show ?case
    using propagate.premis(1) unfolding dpllW-mes-def by (fastforce simp add: lexn-conv assms(2))
next
  case (decided S L)
  have m: map ( $\lambda l. \text{if is-marked } l \text{ then } 2 \text{ else } 1$ ) (rev (trail S))
    @ replicate (card vars – length (trail S)) 3
  = map ( $\lambda l. \text{if is-marked } l \text{ then } 2 \text{ else } 1$ ) (rev (trail S)) @ 3
    # replicate (card vars – Suc (length (trail S))) 3
  using decided.premis[simplified] using Suc-diff-le by fastforce
  then show ?case
    using decided.premis unfolding dpllW-mes-def by (force simp add: lexn-conv assms(2))
next
  case (backtrack S M' L M D)
  have L: is-marked L using backtrack.hyps(2) by auto
  have S: trail S = M' @ L # M
    using backtrack.hyps(1) backtrack-split-list-eq[of trail S] by auto
  show ?case
    using backtrack.premis L unfolding dpllW-mes-def S by (fastforce simp add: lexn-conv assms(2))
qed

```

Proposition theorem 2.8.7 page 73 of CW

lemma *dpll_W-card-decrease'*:

```

assumes dpll: dpllW S S'
and atm-incl: atm-of ' lits-of (trail S)  $\subseteq$  atms-of-msu (clauses S)
and no-dup: no-dup (trail S)
shows (dpllW-mes (trail S') (card (atms-of-msu (clauses S')))),
  (dpllW-mes (trail S) (card (atms-of-msu (clauses S))))  $\in$  lex {(a, b). a < b}

```

proof –

```

have finite (atms-of-msu (clauses S)) unfolding atms-of-ms-def by auto
then have 1: length (trail S)  $\leq$  card (atms-of-msu (clauses S))
  using distinctcard-atm-of-lit-of-eq-length[OF no-dup] atm-incl card-mono by metis

```

moreover

```

have no-dup': no-dup (trail S') using dpll dpllW-distinct-inv no-dup by blast
have SS': clauses S' = clauses S using dpll by (auto dest!: dpllW-same-clauses)
have atm-incl': atm-of ' lits-of (trail S')  $\subseteq$  atms-of-msu (clauses S')
  using atm-incl dpll dpllW-vars-in-snd-inv[OF dpll] by force
have finite (atms-of-msu (clauses S'))
  unfolding atms-of-ms-def by auto
then have 2: length (trail S')  $\leq$  card (atms-of-msu (clauses S'))
  using distinctcard-atm-of-lit-of-eq-length[OF no-dup] atm-incl' card-mono SS' by metis

```

```

ultimately have (dpllW-mes (trail S') (card (atms-of-msu (clauses S')))),
  (dpllW-mes (trail S) (card (atms-of-msu (clauses S))))
 $\in$  lexn {(a, b). a < b} (card (atms-of-msu (clauses S)))
  using dpllW-card-decrease[OF assms(1), of atms-of-msu (clauses S)] by blast
then have (dpllW-mes (trail S') (card (atms-of-msu (clauses S')))),
  (dpllW-mes (trail S) (card (atms-of-msu (clauses S))))  $\in$  lex {(a, b). a < b}

```

unfolding *lex-def* **by** *auto*
then show ($dpll_W\text{-mes}(\text{trail } S')(\text{card}(\text{atms-of-msu}(\text{clauses } S')))$,
 $dpll_W\text{-mes}(\text{trail } S)(\text{card}(\text{atms-of-msu}(\text{clauses } S)))) \in \text{lex } \{(a, b). a < b\}$
using $dpll_W\text{-same-clauses}[OF \text{ assms}(1)]$ **by** *auto*
qed

lemma *wf-lexn*: $wf(\text{lexn } \{(a, b). (a::nat) < b\}(\text{card}(\text{atms-of-msu}(\text{clauses } S))))$
proof –
have $m: \{(a, b). a < b\} = \text{measure id}$ **by** *auto*
show *?thesis* **apply** (*rule wf-lexn*) **unfolding** *m* **by** *auto*
qed

lemma $dpll_W\text{-wf}$:
 $wf \{(S', S). dpll_W\text{-all-inv } S \wedge dpll_W S S'\}$
apply (*rule wf-wf-if-measure'*[*OF wf-lex-less, of - -*
 $\lambda S. dpll_W\text{-mes}(\text{trail } S)(\text{card}(\text{atms-of-msu}(\text{clauses } S))))$])
using $dpll_W\text{-card-decrease'}$ **by** *fast*

lemma $dpll_W\text{-tranclp-star-commute}$:
 $\{(S', S). dpll_W\text{-all-inv } S \wedge dpll_W S S'\}^+ = \{(S', S). dpll_W\text{-all-inv } S \wedge \text{tranclp } dpll_W S S'\}$
(is ?A = ?B)

proof
{ fix $S S'$
assume $(S, S') \in ?A$
then have $(S, S') \in ?B$
by (*induct rule: trancl.induct, auto*)
}
then show $?A \subseteq ?B$ **by** *blast*
{ fix $S S'$
assume $(S, S') \in ?B$
then have $dpll_W^{++} S' S$ **and** $dpll_W\text{-all-inv } S'$ **by** *auto*
then have $(S, S') \in ?A$
proof (*induct rule: tranclp.induct*)
case *r-into-trancl*
then show *?case* **by** (*simp-all add: r-into-trancl'*)
next
case (*trancl-into-trancl* $S S' S''$)
then have $(S', S) \in \{a. \text{case } a \text{ of } (S', S) \Rightarrow dpll_W\text{-all-inv } S \wedge dpll_W S S'\}^+$ **by** *blast*
moreover have $dpll_W\text{-all-inv } S'$
using $\text{rtranclp-}dpll_W\text{-all-inv}[OF \text{ tranclp-into-rtranclp}[OF \text{ trancl-into-trancl.hyps}(1)]]$
 $\text{trancl-into-trancl.prem}$ s **by** *auto*
ultimately have $(S'', S') \in \{(pa, p). dpll_W\text{-all-inv } p \wedge dpll_W p pa\}^+$
using $\langle dpll_W\text{-all-inv } S' \rangle \text{trancl-into-trancl.hyps}(3)$ **by** *blast*
then show *?case*
using $\langle (S', S) \in \{a. \text{case } a \text{ of } (S', S) \Rightarrow dpll_W\text{-all-inv } S \wedge dpll_W S S'\}^+ \rangle$ **by** *auto*
qed
}
then show $?B \subseteq ?A$ **by** *blast*
qed

lemma $dpll_W\text{-wf-tranclp}$: $wf \{(S', S). dpll_W\text{-all-inv } S \wedge dpll_W^{++} S S'\}$
unfolding $dpll_W\text{-tranclp-star-commute}[\text{symmetric}]$ **by** (*simp add: dpll_W-wf wf-trancl*)

lemma $dpll_W\text{-wf-plus}$:

shows wf $\{(S', ([], N)) \mid S'. \text{dpll}_W^{++} ([], N) S'\}$ (is wf ?P)
 apply (rule wf-subset[OF dpll_W-wf-tranclp, of ?P])
 using assms unfolding dpll_W-all-inv-def by auto

16.4 Final States

lemma dpll_W-no-more-step-is-a-conclusive-state:

assumes $\forall S'. \neg \text{dpll}_W S S'$

shows conclusive-dpll_W-state S

proof –

have vars: $\forall s \in \text{atms-of-msu} (\text{clauses } S). s \in \text{atm-of ' lits-of } (\text{trail } S)$

proof (rule ccontr)

assume $\neg (\forall s \in \text{atms-of-msu} (\text{clauses } S). s \in \text{atm-of ' lits-of } (\text{trail } S))$

then obtain L where

L-in-atms: $L \in \text{atms-of-msu} (\text{clauses } S)$ and

L-notin-trail: $L \notin \text{atm-of ' lits-of } (\text{trail } S)$ by metis

obtain L' where $L': \text{atm-of } L' = L$ by (meson literal.sel(2))

then have undefined-lit (trail S) L'

unfolding Marked-Propagated-in-iff-in-lits-of by (metis L-notin-trail atm-of-uminus imageI)

then show False using dpll_W.decided assms(1) L-in-atms L' by blast

qed

show ?thesis

proof (rule ccontr)

assume not-final: $\neg ?thesis$

then have

$\neg \text{trail } S \models_{\text{asm}} \text{clauses } S$ and

$(\exists L \in \text{set } (\text{trail } S). \text{is-marked } L) \vee (\forall C \in \# \text{clauses } S. \neg \text{trail } S \models_{\text{as}} C \text{Not } C)$

unfolding conclusive-dpll_W-state-def by auto

moreover {

assume $\exists L \in \text{set } (\text{trail } S). \text{is-marked } L$

then obtain L M' M where $L: \text{backtrack-split } (\text{trail } S) = (M', L \# M)$

using backtrack-split-some-is-marked-then-snd-has-hd by blast

obtain D where $D \in \# \text{clauses } S$ and $\neg \text{trail } S \models_a D$

using $\langle \neg \text{trail } S \models_{\text{asm}} \text{clauses } S \rangle$ unfolding true-annots-def by auto

then have $\forall s \in \text{atms-of-ms } \{D\}. s \in \text{atm-of ' lits-of } (\text{trail } S)$

using vars unfolding atms-of-ms-def by auto

then have $\text{trail } S \models_{\text{as}} C \text{Not } D$

using all-variables-defined-not-imply-cnot[of D] $\langle \neg \text{trail } S \models_a D \rangle$ by auto

moreover have is-marked L

using L by (metis backtrack-split-snd-hd-marked list.distinct(1) list.sel(1) snd-conv)

ultimately have False

using assms(1) dpll_W.backtrack L $\langle D \in \# \text{clauses } S \rangle \langle \text{trail } S \models_{\text{as}} C \text{Not } D \rangle$ by blast

}

moreover {

assume tr: $\forall C \in \# \text{clauses } S. \neg \text{trail } S \models_{\text{as}} C \text{Not } C$

obtain C where C-in-cls: $C \in \# \text{clauses } S$ and trC: $\neg \text{trail } S \models_a C$

using $\langle \neg \text{trail } S \models_{\text{asm}} \text{clauses } S \rangle$ unfolding true-annots-def by auto

have $\forall s \in \text{atms-of-ms } \{C\}. s \in \text{atm-of ' lits-of } (\text{trail } S)$

using vars $\langle C \in \# \text{clauses } S \rangle$ unfolding atms-of-ms-def by auto

then have $\text{trail } S \models_{\text{as}} C \text{Not } C$

by (meson C-in-cls tr trC all-variables-defined-not-imply-cnot)

then have False using tr C-in-cls by auto

}

ultimately show False by blast

qed

qed

```

lemma dpllW-conclusive-state-correct:
  assumes dpllW** ( $\square$ , N) (M, N) and conclusive-dpllW-state (M, N)
  shows  $M \models_{asm} N \longleftrightarrow \text{satisfiable } (\text{set-mset } N) \text{ (is } ?A \longleftrightarrow ?B)$ 
proof
  let  $?M' = \text{lits-of } M$ 
  assume  $?A$ 
  then have  $?M' \models_{sm} N$  by (simp add: true-annots-true-cls)
  moreover have consistent-interp  $?M'$ 
    using rtranclp-dpllW-inv-starting-from-0[OF assms(1)] by auto
  ultimately show  $?B$  by auto
next
  assume  $?B$ 
  show  $?A$ 
  proof (rule ccontr)
    assume  $n: \neg ?A$ 
    have no-mark:  $\forall L \in \text{set } M. \neg \text{is-marked } L \ \exists C \in \# N. M \models_{as} C \text{Not } C$ 
      using n assms(2) unfolding conclusive-dpllW-state-def by auto
    moreover obtain D where DN:  $D \in \# N$  and MD:  $M \models_{as} C \text{Not } D$  using no-mark by auto
    ultimately have unsatisfiable (set-mset N)
      using only-propagated-vars-unsat rtranclp-dpllW-all-inv[OF assms(1)]
      unfolding dpllW-all-inv-def by force
    then show False using  $\langle ?B \rangle$  by blast
  qed
qed

```

16.5 Link with NOT's DPLL

interpretation *dpll_W-NOT*: *dpll-with-backtrack* .

```

lemma state-eqNOT-iff-eq[iff, simp]: dpllW-NOT.state-eqNOT S T  $\longleftrightarrow S = T$ 
  unfolding dpllW-NOT.state-eqNOT-def by (cases S, cases T) auto

```

```

declare dpllW-NOT.state-simpNOT[simp del]

```

```

lemma dpllW-dpllW-bj:
  assumes inv: dpllW-all-inv S and dpll: dpllW S T
  shows dpllW-NOT.dpll-bj S T
  using dpll inv
  apply (induction rule: dpllW.induct)
    using dpllW-NOT.dpll-bj.simps apply fastforce
    using dpllW-NOT.bj-decideNOT apply fastforce
  apply (frule dpllW-NOT.backtrack.intros[of - - - -], simp-all)
  apply (rule dpllW-NOT.dpll-bj.bj-backjump)
  apply (rule dpllW-NOT.backtrack-is-backjump'',
    simp-all add: dpllW-all-inv-def)
  done

```

```

lemma dpllW-bj-dpll:
  assumes inv: dpllW-all-inv S and dpll: dpllW-NOT.dpll-bj S T
  shows dpllW S T
  using dpll
  apply (induction rule: dpllW-NOT.dpll-bj.induct)
    apply (elim dpllW-NOT.decideE, cases S)
    using decided apply fastforce
  apply (elim dpllW-NOT.propagateE, cases S)

```



```

    using dpllW.simps apply fastforce
apply (elim dpllW-NOT.backjumpE, cases S)
by (simp add: dpllW.simps dpll-with-backtrack.backtrack.simps)

lemma rtrancp-dpllW-rtrancp-dpllW-NOT:
  assumes dpllW** S T and dpllW-all-inv S
  shows dpllW-NOT.dpll-bj** S T
  using assms apply (induction)
  apply simp
  by (smt dpllW-dpllW-bj rtrancp.rtrancp-into-rtrancp rtrancp-dpllW-all-inv)

lemma rtrancp-dpll-rtrancp-dpllW:
  assumes dpllW-NOT.dpll-bj** S T and dpllW-all-inv S
  shows dpllW** S T
  using assms apply (induction)
  apply simp
  by (smt dpllW-bj-dpll rtrancp.rtrancp-into-rtrancp rtrancp-dpllW-all-inv)

lemma dpll-conclusive-state-correctness:
  assumes dpllW-NOT.dpll-bj** ([], N) (M, N) and conclusive-dpllW-state (M, N)
  shows M ⊨asm N ⟷ satisfiable (set-mset N)
proof –
  have dpllW-all-inv ([], N)
  unfolding dpllW-all-inv-def by auto
  show ?thesis
  apply (rule dpllW-conclusive-state-correct)
  apply (simp add: ⟨dpllW-all-inv ([], N)⟩ assms(1) rtrancp-dpll-rtrancp-dpllW)
  using assms(2) by simp
qed

end
theory CDCL-W-Level
imports Partial-Annotated-Clausal-Logic
begin

```

16.5.1 Level of literals and clauses

Getting the level of a variable, implies that the list has to be reversed. Here is the funtion after reversing.

```

fun get-rev-level :: 'v literal ⇒ nat ⇒ ('v, nat, 'a) marked-lits ⇒ nat where
  get-rev-level - - [] = 0 |
  get-rev-level L n (Marked l level # Ls) =
    (if atm-of l = atm-of L then level else get-rev-level L level Ls) |
  get-rev-level L n (Propagated l - # Ls) =
    (if atm-of l = atm-of L then n else get-rev-level L n Ls)

```

abbreviation *get-level* *L M* ≡ *get-rev-level L 0 (rev M)*

```

lemma get-rev-level-uminus[simp]: get-rev-level (−L) n M = get-rev-level L n M
by (induct M arbitrary: n rule: get-rev-level.induct) auto

```

```

lemma atm-of-notin-get-rev-level-eq-0[simp]:
  assumes atm-of L ∉ atm-of ' lits-of M
  shows get-rev-level L n M = 0
  using assms apply (induct M arbitrary: n, simp)

```

by (case-tac a) auto

lemma *get-rev-level-ge-0-atm-of-in*:
assumes *get-rev-level* L n $M > n$
shows *atm-of* $L \in \text{atm-of ' lits-of } M$
using *assms* **apply** (*induct* M *arbitrary*: n , *simp*)
by (case-tac a) *fastforce*+

In *get-rev-level* (resp. *get-level*), the beginning (resp. the end) can be skipped if the literal is not in the beginning (resp. the end).

lemma *get-rev-level-skip[simp]*:
assumes *atm-of* $L \notin \text{atm-of ' lits-of } M$
shows *get-rev-level* L n ($M @ \text{Marked } K i \# M'$) = *get-rev-level* L i ($\text{Marked } K i \# M'$)
using *assms* **apply** (*induct* M *arbitrary*: n i , *simp*)
by (case-tac a) auto

lemma *get-rev-level-notin-end[simp]*:
assumes *atm-of* $L \notin \text{atm-of ' lits-of } M'$
shows *get-rev-level* L n ($M @ M'$) = *get-rev-level* L n M
using *assms* **apply** (*induct* M *arbitrary*: n , *simp*)
by (case-tac a) auto

If the literal is at the beginning, then the end can be skipped

lemma *get-rev-level-skip-end[simp]*:
assumes *atm-of* $L \in \text{atm-of ' lits-of } M$
shows *get-rev-level* L n ($M @ M'$) = *get-rev-level* L n M
using *assms* **apply** (*induct* M *arbitrary*: n , *simp*)
by (case-tac a) auto

lemma *get-level-skip-beginning*:
assumes *atm-of* $L' \neq \text{atm-of (lit-of } K)$
shows *get-level* L' ($K \# M$) = *get-level* L' M
using *assms* **by** auto

lemma *get-level-skip-beginning-not-marked-rev*:
assumes *atm-of* $L \notin \text{atm-of ' lit-of ' (set } S)$
and $\forall s \in \text{set } S. \neg \text{is-marked } s$
shows *get-level* L ($M @ \text{rev } S$) = *get-level* L M
using *assms* **by** (*induction* S *rule*: *marked-lit-list-induct*) auto

lemma *get-level-skip-beginning-not-marked[simp]*:
assumes *atm-of* $L \notin \text{atm-of ' lit-of ' (set } S)$
and $\forall s \in \text{set } S. \neg \text{is-marked } s$
shows *get-level* L ($M @ S$) = *get-level* L M
using *get-level-skip-beginning-not-marked-rev*[*of* L *rev* S M] *assms* **by** auto

lemma *get-rev-level-skip-beginning-not-marked[simp]*:
assumes *atm-of* $L \notin \text{atm-of ' lit-of ' (set } S)$
and $\forall s \in \text{set } S. \neg \text{is-marked } s$
shows *get-rev-level* L 0 (*rev* $S @ \text{rev } M$) = *get-level* L M
using *get-level-skip-beginning-not-marked-rev*[*of* L *rev* S M] *assms* **by** auto

lemma *get-level-skip-in-all-not-marked*:
fixes $M :: ('a, \text{nat}, 'b) \text{ marked-lit list}$ **and** $L :: 'a \text{ literal}$
assumes $\forall m \in \text{set } M. \neg \text{is-marked } m$

and $\text{atm-of } L \in \text{atm-of 'lit-of ' (set } M)$
shows $\text{get-rev-level } L \ n \ M = n$
proof –
show *?thesis*
using *assms* **by** (*induction* M *rule*: *marked-lit-list-induct*) *auto*
qed

lemma *get-level-skip-all-not-marked[simp]*:
fixes M
defines $M' \equiv \text{rev } M$
assumes $\forall m \in \text{set } M. \neg \text{is-marked } m$
shows $\text{get-level } L \ M = 0$
proof –
have $M: M = \text{rev } M'$
unfolding $M'\text{-def}$ **by** *auto*
show *?thesis*
using *assms* **unfolding** M **by** (*induction* M' *rule*: *marked-lit-list-induct*) *auto*
qed

abbreviation $\text{MMax } M \equiv \text{Max (set-mset } M)$

the $\{\#0::'a\# \}$ is there to ensures that the set is not empty.

definition $\text{get-maximum-level} :: 'a \text{ literal multiset} \Rightarrow ('a, \text{nat}, 'b) \text{ marked-lit list} \Rightarrow \text{nat}$
where
 $\text{get-maximum-level } D \ M = \text{MMax } (\{\#0\# \} + \text{image-mset } (\lambda L. \text{get-level } L \ M) \ D)$

lemma *get-maximum-level-ge-get-level*:
 $L \in \# \ D \Longrightarrow \text{get-maximum-level } D \ M \geq \text{get-level } L \ M$
unfolding *get-maximum-level-def* **by** *auto*

lemma *get-maximum-level-empty[simp]*:
 $\text{get-maximum-level } \{\#\} \ M = 0$
unfolding *get-maximum-level-def* **by** *auto*

lemma *get-maximum-level-exists-lit-of-max-level*:
 $D \neq \{\#\} \Longrightarrow \exists L \in \# \ D. \text{get-level } L \ M = \text{get-maximum-level } D \ M$
unfolding *get-maximum-level-def*
apply (*induct* D)
apply *simp*
by (*case-tac* $D = \{\#\}$) (*auto simp add*: *max-def*)

lemma *get-maximum-level-empty-list[simp]*:
 $\text{get-maximum-level } D \ [] = 0$
unfolding *get-maximum-level-def* **by** (*simp add*: *image-constant-conv*)

lemma *get-maximum-level-single[simp]*:
 $\text{get-maximum-level } \{\#L\# \} \ M = \text{get-level } L \ M$
unfolding *get-maximum-level-def* **by** *simp*

lemma *get-maximum-level-plus*:
 $\text{get-maximum-level } (D + D') \ M = \max (\text{get-maximum-level } D \ M) (\text{get-maximum-level } D' \ M)$
by (*induct* D) (*auto simp add*: *get-maximum-level-def*)

lemma *get-maximum-level-exists-lit*:
assumes $n: n > 0$
and $\text{max}: \text{get-maximum-level } D \ M = n$
shows $\exists L \in \#D. \text{get-level } L \ M = n$
proof –
have $f: \text{finite } (\text{insert } 0 ((\lambda L. \text{get-level } L \ M) \text{ 'set-mset } D))$ **by** *auto*
hence $n \in ((\lambda L. \text{get-level } L \ M) \text{ 'set-mset } D)$
using $n \ \text{max} \ \text{Max-in}[OF \ f]$ **unfolding** *get-maximum-level-def* **by** *simp*
thus $\exists L \in \#D. \text{get-level } L \ M = n$ **by** *auto*
qed

lemma *get-maximum-level-skip-first[simp]*:
assumes $\text{atm-of } L \notin \text{atms-of } D$
shows $\text{get-maximum-level } D \ (\text{Propagated } L \ C \ \# \ M) = \text{get-maximum-level } D \ M$
using *assms* **unfolding** *get-maximum-level-def* *atms-of-def*
 $\text{atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set}$
by (*smt atm-of-in-atm-of-set-in-uminus get-level-skip-beginning image-iff marked-lit.sel(2)*
 $\text{multiset.map-cong0}$)

lemma *get-maximum-level-skip-beginning*:
assumes $DH: \text{atms-of } D \subseteq \text{atm-of 'lits-of } H$
shows $\text{get-maximum-level } D \ (c \ @ \ \text{Marked } Kh \ i \ \# \ H) = \text{get-maximum-level } D \ H$
proof –
have $(\lambda L. \text{get-rev-level } L \ 0 \ (\text{rev } H \ @ \ \text{Marked } Kh \ i \ \# \ \text{rev } c)) \text{ 'set-mset } D$
 $= (\lambda L. \text{get-rev-level } L \ 0 \ (\text{rev } H)) \text{ 'set-mset } D$
using DH **unfolding** *atms-of-def*
by (*metis (no-types, lifting) get-rev-level-skip-end image-cong image-subset-iff lits-of-rev*)
thus *?thesis* **using** DH **unfolding** *get-maximum-level-def* **by** *auto*
qed

lemma *get-maximum-level-D-single-propagated*:
 $\text{get-maximum-level } D \ [\text{Propagated } x21 \ x22] = 0$
proof –
have $A: \text{insert } 0 ((\lambda L. 0) \text{ 'set-mset } D \cap \{L. \text{atm-of } x21 = \text{atm-of } L\})$
 $\cup (\lambda L. 0) \text{ 'set-mset } D \cap \{L. \text{atm-of } x21 \neq \text{atm-of } L\}) = \{0\}$
by *auto*
show *?thesis* **unfolding** *get-maximum-level-def* **by** (*simp add: A*)
qed

lemma *get-maximum-level-skip-notin*:
assumes $D: \forall L \in \#D. \text{atm-of } L \in \text{atm-of 'lits-of } M$
shows $\text{get-maximum-level } D \ M = \text{get-maximum-level } D \ (\text{Propagated } x21 \ x22 \ \# \ M)$
proof –
have $A: (\lambda L. \text{get-rev-level } L \ 0 \ (\text{rev } M \ @ \ [\text{Propagated } x21 \ x22])) \text{ 'set-mset } D$
 $= (\lambda L. \text{get-rev-level } L \ 0 \ (\text{rev } M)) \text{ 'set-mset } D$
using D **by** (*auto intro!: image-cong simp add: lits-of-def*)
show *?thesis* **unfolding** *get-maximum-level-def* **by** (*auto simp add: A*)
qed

lemma *get-maximum-level-skip-un-marked-not-present*:
assumes $\forall L \in \#D. \text{atm-of } L \in \text{atm-of 'lits-of } aa$ **and**
 $\forall m \in \text{set } M. \neg \text{is-marked } m$
shows $\text{get-maximum-level } D \ aa = \text{get-maximum-level } D \ (M \ @ \ aa)$
using *assms* **apply** (*induction M*)
apply *simp*

```

by (case-tac a) (auto intro!: get-maximum-level-skip-notin[of D - @ aa] simp add: image-Un)

fun get-maximum-possible-level:: ('b, nat, 'c) marked-lit list ⇒ nat  where
get-maximum-possible-level [] = 0 |
get-maximum-possible-level (Marked K i # l) = max i (get-maximum-possible-level l) |
get-maximum-possible-level (Propagated - - # l) = get-maximum-possible-level l

lemma get-maximum-possible-level-append[simp]:
  get-maximum-possible-level (M@M')
    = max (get-maximum-possible-level M) (get-maximum-possible-level M')
  apply (induct M, simp) by (case-tac a, auto)

lemma get-maximum-possible-level-rev[simp]:
  get-maximum-possible-level (rev M) = get-maximum-possible-level M
  apply (induct M, simp) by (case-tac a, auto)

lemma get-maximum-possible-level-ge-get-rev-level:
  max (get-maximum-possible-level M) i ≥ get-rev-level L i M
  apply (induct M arbitrary: i)
  apply simp
  by (case-tac a) (auto simp add: le-max-iff-disj)

lemma get-maximum-possible-level-ge-get-level[simp]:
  get-maximum-possible-level M ≥ get-level L M
  using get-maximum-possible-level-ge-get-rev-level[of - 0 rev -] by auto

lemma get-maximum-possible-level-ge-get-maximum-level[simp]:
  get-maximum-possible-level M ≥ get-maximum-level D M
  using get-maximum-level-exists-lit-of-max-level unfolding Bex-mset-def
  by (metis get-maximum-level-empty get-maximum-possible-level-ge-get-level le0)

fun get-all-mark-of-propagated where
get-all-mark-of-propagated [] = [] |
get-all-mark-of-propagated (Marked - - # L) = get-all-mark-of-propagated L |
get-all-mark-of-propagated (Propagated - mark # L) = mark # get-all-mark-of-propagated L

lemma get-all-mark-of-propagated-append[simp]: get-all-mark-of-propagated (A @ B) = get-all-mark-of-propagated
A @ get-all-mark-of-propagated B
  apply (induct A, simp)
  by (case-tac a) auto



### 16.5.2 Properties about the levels



fun get-all-levels-of-marked:: ('b, 'a, 'c) marked-lit list ⇒ 'a list  where
get-all-levels-of-marked [] = [] |
get-all-levels-of-marked (Marked l level # Ls) = level # get-all-levels-of-marked Ls |
get-all-levels-of-marked (Propagated - - # Ls) = get-all-levels-of-marked Ls

lemma get-all-levels-of-marked-nil-iff-not-is-marked:
  get-all-levels-of-marked xs = [] ⟷ (∀ x ∈ set xs. ¬is-marked x)
  using assms by (induction xs rule: marked-lit-list-induct) auto

lemma get-all-levels-of-marked-cons:
  get-all-levels-of-marked (a # b) =
    (if is-marked a then [level-of a] else []) @ get-all-levels-of-marked b
  by (case-tac a) simp-all

```

lemma *get-all-levels-of-marked-append[simp]:*
 $\text{get-all-levels-of-marked } (a @ b) = \text{get-all-levels-of-marked } a @ \text{get-all-levels-of-marked } b$
by (induct a) (simp-all add: get-all-levels-of-marked-cons)

lemma *in-get-all-levels-of-marked-iff-decomp:*
 $i \in \text{set } (\text{get-all-levels-of-marked } M) \longleftrightarrow (\exists c K c'. M = c @ \text{Marked } K i \# c') \text{ (is } ?A \longleftrightarrow ?B)$

proof
assume ?B
thus ?A **by** auto

next
assume ?A
thus ?B
apply (induction M rule: marked-lit-list-induct)
apply auto[]
apply (metis append-Cons append-Nil get-all-levels-of-marked.simps(2) set-ConsD)
by (metis append-Cons get-all-levels-of-marked.simps(3))

qed

lemma *get-rev-level-less-max-get-all-levels-of-marked:*
 $\text{get-rev-level } L \ n \ M \leq \text{Max } (\text{set } (n \# \text{get-all-levels-of-marked } M))$
by (induct M arbitrary: n rule: get-all-levels-of-marked.induct)
(simp-all add: max.coboundedI2)

lemma *get-rev-level-ge-min-get-all-levels-of-marked:*
assumes atm-of L \in atm-of ' lits-of M
shows $\text{get-rev-level } L \ n \ M \geq \text{Min } (\text{set } (n \# \text{get-all-levels-of-marked } M))$
using assms **by** (induct M arbitrary: n rule: get-all-levels-of-marked.induct)
(auto simp add: min-le-iff-disj)

lemma *get-all-levels-of-marked-rev-eq-rev-get-all-levels-of-marked[simp]:*
 $\text{get-all-levels-of-marked } (\text{rev } M) = \text{rev } (\text{get-all-levels-of-marked } M)$
by (induct M rule: get-all-levels-of-marked.induct)
(simp-all add: max.coboundedI2)

lemma *get-maximum-possible-level-max-get-all-levels-of-marked:*
 $\text{get-maximum-possible-level } M = \text{Max } (\text{insert } 0 \ (\text{set } (\text{get-all-levels-of-marked } M)))$
apply (induct M, simp)
by (case-tac a) (case-tac set (get-all-levels-of-marked M) = {}, auto)

lemma *get-rev-level-in-levels-of-marked:*
 $\text{get-rev-level } L \ n \ M \in \{0, n\} \cup \text{set } (\text{get-all-levels-of-marked } M)$
apply (induction M arbitrary: n)
apply auto[1]
by (case-tac a)
(force simp add: atm-of-eq-atm-of)+

lemma *get-rev-level-in-atms-in-levels-of-marked:*
 $\text{atm-of } L \in \text{atm-of ' } (\text{lits-of } M) \implies \text{get-rev-level } L \ n \ M \in \{n\} \cup \text{set } (\text{get-all-levels-of-marked } M)$
apply (induction M arbitrary: n, simp)
by (case-tac a)
(auto simp add: atm-of-eq-atm-of)

lemma *get-all-levels-of-marked-no-marked:*

($\forall l \in \text{set } Ls. \neg \text{is-marked } l$) \longleftrightarrow $\text{get-all-levels-of-marked } Ls = []$
by (induction Ls) (auto simp add: get-all-levels-of-marked-cons)

lemma *get-level-in-levels-of-marked*:
 $\text{get-level } L \ M \in \{0\} \cup \text{set } (\text{get-all-levels-of-marked } M)$
using *get-rev-level-in-levels-of-marked*[of $L \ 0 \ \text{rev } M$] **by** auto

The zero is here to avoid empty-list issues with *last*:

lemma *get-level-get-rev-level-get-all-levels-of-marked*:
assumes $\text{atm-of } L \notin \text{atm-of } (\text{lits-of } M)$
shows $\text{get-level } L \ (K @ M) = \text{get-rev-level } L \ (\text{last } (0 \# \text{get-all-levels-of-marked } (\text{rev } M)))$
 $(\text{rev } K)$
using *assms*
proof (induct M arbitrary: K)
case *Nil*
thus ?case **by** auto
next
case ($\text{Cons } a \ M$)
hence $H: \bigwedge K. \text{get-level } L \ (K @ M)$
 $= \text{get-rev-level } L \ (\text{last } (0 \# \text{get-all-levels-of-marked } (\text{rev } M))) \ (\text{rev } K)$
by auto
have $\text{get-level } L \ ((K @ [a]) @ M)$
 $= \text{get-rev-level } L \ (\text{last } (0 \# \text{get-all-levels-of-marked } (\text{rev } M))) \ (a \# \text{rev } K)$
using $H[\text{of } K @ [a]]$ **by** simp
thus ?case **using** *Cons(2)* **by** (case-tac a) auto
qed

lemma *get-rev-level-can-skip-correctly-ordered*:
assumes *no-dup* M
and $\text{atm-of } L \notin \text{atm-of } (\text{lits-of } M)$
and $\text{get-all-levels-of-marked } M = \text{rev } [\text{Suc } 0 .. < \text{Suc } (\text{length } (\text{get-all-levels-of-marked } M))]$
shows $\text{get-rev-level } L \ 0 \ (\text{rev } M @ K) = \text{get-rev-level } L \ (\text{length } (\text{get-all-levels-of-marked } M)) \ K$
using *assms*
proof (induct M arbitrary: K)
case *Nil*
thus ?case **by** simp
next
case ($\text{Cons } a \ M \ K$)
show ?case
proof (case-tac a)
fix $L' \ i$
assume $a: a = \text{Marked } L' \ i$
have $i: i = \text{Suc } (\text{length } (\text{get-all-levels-of-marked } M))$
and $\text{get-all-levels-of-marked } M = \text{rev } [\text{Suc } 0 .. < \text{Suc } (\text{length } (\text{get-all-levels-of-marked } M))]$
using *Cons.prem(3)* **unfolding** a **by** auto
hence $\text{get-rev-level } L \ 0 \ (\text{rev } M @ (a \# K))$
 $= \text{get-rev-level } L \ (\text{length } (\text{get-all-levels-of-marked } M)) \ (a \# K)$
using *Cons.hyps* *Cons.prem* **by** auto
thus ?case **using** *Cons.prem(2)* **unfolding** $a \ i$ **by** auto
next
fix $L' \ D$
assume $a: a = \text{Propagated } L' \ D$
have $\text{get-all-levels-of-marked } M = \text{rev } [\text{Suc } 0 .. < \text{Suc } (\text{length } (\text{get-all-levels-of-marked } M))]$
using *Cons.prem(3)* **unfolding** a **by** auto
hence $\text{get-rev-level } L \ 0 \ (\text{rev } M @ (a \# K))$

```

      = get-rev-level L (length (get-all-levels-of-marked M)) (a # K)
    using Cons by auto
  thus ?case using Cons.premis(2) unfolding a by auto
qed
qed

lemma get-level-skip-beginning-hd-get-all-levels-of-marked:
  assumes atm-of L  $\notin$  atm-of ' lits-of S
  and get-all-levels-of-marked S  $\neq$  []
  shows get-level L (M@ S) = get-rev-level L (hd (get-all-levels-of-marked S)) (rev M)
  using assms
proof (induction S arbitrary: M rule: marked-lit-list-induct)
  case nil
  thus ?case by (auto simp add: lits-of-def)
next
  case (marked K m) note notin = this(2)
  thus ?case by (auto simp add: lits-of-def)
next
  case (proped L l) note IH = this(1) and L = this(2) and neq = this(3)
  show ?case using IH[of M@[Propagated L l]] L neq by (auto simp add: atm-of-eq-atm-of)
qed

end
theory CDCL-W
imports Partial-Annotated-Clausal-Logic List-More CDCL-W-Level Wellfounded-More

begin
declare set-mset-minus-replicate-mset[simp]

lemma Bex-set-set-Bex-set[iff]:  $(\exists x \in \text{set-mset } C. P) \longleftrightarrow (\exists x \in \#C. P)$ 
  by auto

```

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```

sledgehammer-params[verbose, e spass cvc4 z3 verit]
declare upt.simps(2)[simp del]

```

```

datatype 'a conflicting-clause = C-True | C-Clause 'a

```

17.1 The State

```

locale stateW =
  fixes
    trail :: 'st  $\Rightarrow$  ('v, nat, 'v clause) marked-lits and
    init-clss :: 'st  $\Rightarrow$  'v clauses and
    learned-clss :: 'st  $\Rightarrow$  'v clauses and
    backtrack-lvl :: 'st  $\Rightarrow$  nat and
    conflicting :: 'st  $\Rightarrow$  'v clause conflicting-clause and

    cons-trail :: ('v, nat, 'v clause) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
    tl-trail :: 'st  $\Rightarrow$  'st and
    add-init-cls :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
    add-learned-cls :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
    remove-cls :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and

```


update-backtrack-lvl :: *nat* \Rightarrow '*st* \Rightarrow '*st* **and**
update-conflicting :: '*v* *clause* *conflicting-clause* \Rightarrow '*st* \Rightarrow '*st* **and**

init-state :: '*v* *clauses* \Rightarrow '*st* **and**
restart-state :: '*st* \Rightarrow '*st*

assumes

trail-cons-trail[simp]:

$\bigwedge L \text{ st. } \text{undefined-lit} (\text{trail st}) (\text{lit-of } L) \Longrightarrow \text{trail} (\text{cons-trail } L \text{ st}) = L \# \text{trail st}$ **and**

trail-tl-trail[simp]: $\bigwedge \text{st. trail} (\text{tl-trail st}) = \text{tl} (\text{trail st})$ **and**

trail-add-init-cls[simp]:

$\bigwedge \text{st } C. \text{no-dup} (\text{trail st}) \Longrightarrow \text{trail} (\text{add-init-cls } C \text{ st}) = \text{trail st}$ **and**

trail-add-learned-cls[simp]:

$\bigwedge C \text{ st. no-dup} (\text{trail st}) \Longrightarrow \text{trail} (\text{add-learned-cls } C \text{ st}) = \text{trail st}$ **and**

trail-remove-cls[simp]:

$\bigwedge C \text{ st. trail} (\text{remove-cls } C \text{ st}) = \text{trail st}$ **and**

trail-update-backtrack-lvl[simp]: $\bigwedge \text{st } C. \text{trail} (\text{update-backtrack-lvl } C \text{ st}) = \text{trail st}$ **and**

trail-update-conflicting[simp]: $\bigwedge C \text{ st. trail} (\text{update-conflicting } C \text{ st}) = \text{trail st}$ **and**

init-clss-cons-trail[simp]:

$\bigwedge M \text{ st. } \text{undefined-lit} (\text{trail st}) (\text{lit-of } M) \Longrightarrow \text{init-clss} (\text{cons-trail } M \text{ st}) = \text{init-clss st}$ **and**

init-clss-tl-trail[simp]:

$\bigwedge \text{st. init-clss} (\text{tl-trail st}) = \text{init-clss st}$ **and**

init-clss-add-init-cls[simp]:

$\bigwedge \text{st } C. \text{no-dup} (\text{trail st}) \Longrightarrow \text{init-clss} (\text{add-init-cls } C \text{ st}) = \{\#C\# \} + \text{init-clss st}$ **and**

init-clss-add-learned-cls[simp]:

$\bigwedge C \text{ st. no-dup} (\text{trail st}) \Longrightarrow \text{init-clss} (\text{add-learned-cls } C \text{ st}) = \text{init-clss st}$ **and**

init-clss-remove-cls[simp]:

$\bigwedge C \text{ st. init-clss} (\text{remove-cls } C \text{ st}) = \text{remove-mset } C (\text{init-clss st})$ **and**

init-clss-update-backtrack-lvl[simp]:

$\bigwedge \text{st } C. \text{init-clss} (\text{update-backtrack-lvl } C \text{ st}) = \text{init-clss st}$ **and**

init-clss-update-conflicting[simp]:

$\bigwedge C \text{ st. init-clss} (\text{update-conflicting } C \text{ st}) = \text{init-clss st}$ **and**

learned-clss-cons-trail[simp]:

$\bigwedge M \text{ st. } \text{undefined-lit} (\text{trail st}) (\text{lit-of } M) \Longrightarrow$
 $\text{learned-clss} (\text{cons-trail } M \text{ st}) = \text{learned-clss st}$ **and**

learned-clss-tl-trail[simp]:

$\bigwedge \text{st. learned-clss} (\text{tl-trail st}) = \text{learned-clss st}$ **and**

learned-clss-add-init-cls[simp]:

$\bigwedge \text{st } C. \text{no-dup} (\text{trail st}) \Longrightarrow \text{learned-clss} (\text{add-init-cls } C \text{ st}) = \text{learned-clss st}$ **and**

learned-clss-add-learned-cls[simp]:

$\bigwedge C \text{ st. no-dup} (\text{trail st}) \Longrightarrow \text{learned-clss} (\text{add-learned-cls } C \text{ st}) = \{\#C\# \} + \text{learned-clss st}$
and

learned-clss-remove-cls[simp]:

$\bigwedge C \text{ st. learned-clss} (\text{remove-cls } C \text{ st}) = \text{remove-mset } C (\text{learned-clss st})$ **and**

learned-clss-update-backtrack-lvl[simp]:

$\bigwedge \text{st } C. \text{learned-clss} (\text{update-backtrack-lvl } C \text{ st}) = \text{learned-clss st}$ **and**

learned-clss-update-conflicting[simp]:

$\bigwedge C \text{ st. learned-clss} (\text{update-conflicting } C \text{ st}) = \text{learned-clss st}$ **and**

backtrack-lvl-cons-trail[simp]:

$\bigwedge M \text{ st. } \text{undefined-lit} (\text{trail st}) (\text{lit-of } M) \Longrightarrow$
 $\text{backtrack-lvl} (\text{cons-trail } M \text{ st}) = \text{backtrack-lvl st}$ **and**

backtrack-lvl-tl-trail[simp]:

$\bigwedge \text{st. backtrack-lvl} (\text{tl-trail st}) = \text{backtrack-lvl st}$ **and**

backtrack-lvl-add-init-cls[simp]:

$\bigwedge st\ C. no_dup\ (trail\ st) \implies backtrack_lvl\ (add_init_cls\ C\ st) = backtrack_lvl\ st$ **and**
backtrack-lvl-add-learned-cls[simp]:

$\bigwedge C\ st. no_dup\ (trail\ st) \implies backtrack_lvl\ (add_learned_cls\ C\ st) = backtrack_lvl\ st$ **and**
backtrack-lvl-remove-cls[simp]:

$\bigwedge C\ st. backtrack_lvl\ (remove_cls\ C\ st) = backtrack_lvl\ st$ **and**
backtrack-lvl-update-backtrack-lvl[simp]:

$\bigwedge st\ k. backtrack_lvl\ (update_backtrack_lvl\ k\ st) = k$ **and**
backtrack-lvl-update-conflicting[simp]:

$\bigwedge C\ st. backtrack_lvl\ (update_conflicting\ C\ st) = backtrack_lvl\ st$ **and**

conflicting-cons-trail[simp]:

$\bigwedge M\ st. undefined_lit\ (trail\ st)\ (lit_of\ M) \implies$
 $conflicting\ (cons_trail\ M\ st) = conflicting\ st$ **and**

conflicting-tl-trail[simp]:

$\bigwedge st. conflicting\ (tl_trail\ st) = conflicting\ st$ **and**

conflicting-add-init-cls[simp]:

$\bigwedge st\ C. no_dup\ (trail\ st) \implies conflicting\ (add_init_cls\ C\ st) = conflicting\ st$ **and**

conflicting-add-learned-cls[simp]:

$\bigwedge C\ st. no_dup\ (trail\ st) \implies conflicting\ (add_learned_cls\ C\ st) = conflicting\ st$ **and**

conflicting-remove-cls[simp]:

$\bigwedge C\ st. conflicting\ (remove_cls\ C\ st) = conflicting\ st$ **and**

conflicting-update-backtrack-lvl[simp]:

$\bigwedge st\ C. conflicting\ (update_backtrack_lvl\ C\ st) = conflicting\ st$ **and**

conflicting-update-conflicting[simp]:

$\bigwedge C\ st. conflicting\ (update_conflicting\ C\ st) = C$ **and**

init-state-trail[simp]: $\bigwedge N. trail\ (init_state\ N) = []$ **and**

init-state-clss[simp]: $\bigwedge N. init_clss\ (init_state\ N) = N$ **and**

init-state-learned-clss[simp]: $\bigwedge N. learned_clss\ (init_state\ N) = \{\#\}$ **and**

init-state-backtrack-lvl[simp]: $\bigwedge N. backtrack_lvl\ (init_state\ N) = 0$ **and**

init-state-conflicting[simp]: $\bigwedge N. conflicting\ (init_state\ N) = C_True$ **and**

trail-restart-state[simp]: $trail\ (restart_state\ S) = []$ **and**

init-clss-restart-state[simp]: $init_clss\ (restart_state\ S) = init_clss\ S$ **and**

learned-clss-restart-state[intro]: $learned_clss\ (restart_state\ S) \subseteq\# learned_clss\ S$ **and**

backtrack-lvl-restart-state[simp]: $backtrack_lvl\ (restart_state\ S) = 0$ **and**

conflicting-restart-state[simp]: $conflicting\ (restart_state\ S) = C_True$

begin

definition *clauses* :: '*st* \Rightarrow '*v* clauses **where**

clauses *S* = *init-clss* *S* + *learned-clss* *S*

lemma

shows

clauses-cons-trail[simp]:

$undefined_lit\ (trail\ S)\ (lit_of\ M) \implies clauses\ (cons_trail\ M\ S) = clauses\ S$ **and**

clauses-tl-trail[simp]: $clauses\ (tl_trail\ S) = clauses\ S$ **and**

clauses-add-learned-cls-unfolded:

$no_dup\ (trail\ S) \implies clauses\ (add_learned_cls\ U\ S) = \{\#U\#\} + learned_clss\ S + init_clss\ S$
and

clauses-add-init-cls[simp]:

$no_dup\ (trail\ S) \implies clauses\ (add_init_cls\ N\ S) = \{\#N\#\} + init_clss\ S + learned_clss\ S$ **and**

clauses-update-backtrack-lvl[simp]: $clauses\ (update_backtrack_lvl\ k\ S) = clauses\ S$ **and**

clauses-update-conflicting[simp]: $clauses\ (update_conflicting\ D\ S) = clauses\ S$ **and**

clauses-remove-cls[simp]:
 $\text{clauses } (\text{remove-cl } C \ S) = \text{clauses } S - \text{replicate-mset } (\text{count } (\text{clauses } S) \ C) \ C \text{ and}$
clauses-add-learned-cls[simp]:
 $\text{no-dup } (\text{trail } S) \implies \text{clauses } (\text{add-learned-cl } C \ S) = \{\#C\# \} + \text{clauses } S \text{ and}$
clauses-restart[simp]: $\text{clauses } (\text{restart-state } S) \subseteq \# \text{ clauses } S \text{ and}$
clauses-init-state[simp]: $\bigwedge N. \text{ clauses } (\text{init-state } N) = N$
prefer 9 using *clauses-def* *learned-clss-restart-state* **apply** *fastforce*
by (*auto simp: ac-simps replicate-mset-plus clauses-def intro: multiset-eqI*)

abbreviation *state* :: '*st* \Rightarrow ('*v*, nat, '*v* clause) marked-lit list \times '*v* clauses \times '*v* clauses
 \times nat \times '*v* clause conflicting-clause **where**
state *S* \equiv (*trail* *S*, *init-clss* *S*, *learned-clss* *S*, *backtrack-lvl* *S*, *conflicting* *S*)

abbreviation *incr-lvl* :: '*st* \Rightarrow '*st* **where**
incr-lvl *S* \equiv *update-backtrack-lvl* (*backtrack-lvl* *S* + 1) *S*

definition *state-eq* :: '*st* \Rightarrow '*st* \Rightarrow bool (**infix** \sim 50) **where**
 $S \sim T \iff \text{state } S = \text{state } T$

lemma *state-eq-ref*[*simp*, *intro*]:
 $S \sim S$
unfolding *state-eq-def* **by** *auto*

lemma *state-eq-sym*:
 $S \sim T \iff T \sim S$
unfolding *state-eq-def* **by** *auto*

lemma *state-eq-trans*:
 $S \sim T \implies T \sim U \implies S \sim U$
unfolding *state-eq-def* **by** *auto*

lemma
shows
state-eq-trail: $S \sim T \implies \text{trail } S = \text{trail } T$ **and**
state-eq-init-clss: $S \sim T \implies \text{init-clss } S = \text{init-clss } T$ **and**
state-eq-learned-clss: $S \sim T \implies \text{learned-clss } S = \text{learned-clss } T$ **and**
state-eq-backtrack-lvl: $S \sim T \implies \text{backtrack-lvl } S = \text{backtrack-lvl } T$ **and**
state-eq-conflicting: $S \sim T \implies \text{conflicting } S = \text{conflicting } T$ **and**
state-eq-clauses: $S \sim T \implies \text{clauses } S = \text{clauses } T$ **and**
state-eq-undefined-lit: $S \sim T \implies \text{undefined-lit } (\text{trail } S) \ L = \text{undefined-lit } (\text{trail } T) \ L$
unfolding *state-eq-def* *clauses-def* **by** *auto*

lemmas *state-simp*[*simp*] = *state-eq-trail* *state-eq-init-clss* *state-eq-learned-clss*
state-eq-backtrack-lvl *state-eq-conflicting* *state-eq-clauses* *state-eq-undefined-lit*

lemma *atms-of-ms-learned-clss-restart-state-in-atms-of-ms-learned-clssI*[*intro*]:
 $x \in \text{atms-of-msu } (\text{learned-clss } (\text{restart-state } S)) \implies x \in \text{atms-of-msu } (\text{learned-clss } S)$
by (*meson atms-of-ms-mono learned-clss-restart-state set-mset-mono subsetCE*)

function *reduce-trail-to* :: ('*v*, nat, '*v* clause) marked-lits \Rightarrow '*st* \Rightarrow '*st* **where**
reduce-trail-to *F* *S* =
 (if *length* (*trail* *S*) = *length* *F* \vee *trail* *S* = [] then *S* else *reduce-trail-to* *F* (*tl-trail* *S*))
by *fast+*
termination

by (relation measure ($\lambda(-, S). \text{length } (\text{trail } S)$)) simp-all

declare reduce-trail-to.simps[simp del]

lemma
shows
 reduce-trail-to-nil[simp]: $\text{trail } S = [] \implies \text{reduce-trail-to } F S = S$ **and**
 reduce-trail-to-eq-length[simp]: $\text{length } (\text{trail } S) = \text{length } F \implies \text{reduce-trail-to } F S = S$
by (auto simp: reduce-trail-to.simps)

lemma reduce-trail-to-length-ne:
 $\text{length } (\text{trail } S) \neq \text{length } F \implies \text{trail } S \neq [] \implies$
 $\text{reduce-trail-to } F S = \text{reduce-trail-to } F (\text{tl-trail } S)$
by (auto simp: reduce-trail-to.simps)

lemma trail-reduce-trail-to-length-le:
assumes $\text{length } F > \text{length } (\text{trail } S)$
shows $\text{trail } (\text{reduce-trail-to } F S) = []$
using assms **apply** (induction $F S$ rule: reduce-trail-to.induct)
by (metis (no-types, hide-lams) length-tl less-imp-diff-less less-irrefl trail-tl-trail
 reduce-trail-to.simps)

lemma trail-reduce-trail-to-nil[simp]:
 $\text{trail } (\text{reduce-trail-to } [] S) = []$
apply (induction []:: ('v, nat, 'v clause) marked-lits S rule: reduce-trail-to.induct)
by (metis length-0-conv reduce-trail-to-length-ne reduce-trail-to-nil)

lemma clauses-reduce-trail-to-nil:
 $\text{clauses } (\text{reduce-trail-to } [] S) = \text{clauses } S$
apply (induction []:: ('v, nat, 'v clause) marked-lits S rule: reduce-trail-to.induct)
by (metis clauses-tl-trail reduce-trail-to.simps)

lemma reduce-trail-to-skip-beginning:
assumes $\text{trail } S = F' @ F$
shows $\text{trail } (\text{reduce-trail-to } F S) = F$
using assms **by** (induction F' arbitrary: S) (auto simp: reduce-trail-to-length-ne)

lemma clauses-reduce-trail-to[simp]:
 $\text{clauses } (\text{reduce-trail-to } F S) = \text{clauses } S$
apply (induction $F S$ rule: reduce-trail-to.induct)
by (metis clauses-tl-trail reduce-trail-to.simps)

lemma conflicting-update-trial[simp]:
 $\text{conflicting } (\text{reduce-trail-to } F S) = \text{conflicting } S$
apply (induction $F S$ rule: reduce-trail-to.induct)
by (metis conflicting-tl-trail reduce-trail-to.simps)

lemma backtrack-lvl-update-trial[simp]:
 $\text{backtrack-lvl } (\text{reduce-trail-to } F S) = \text{backtrack-lvl } S$
apply (induction $F S$ rule: reduce-trail-to.induct)
by (metis backtrack-lvl-tl-trail reduce-trail-to.simps)

lemma init-clss-update-trial[simp]:
 $\text{init-clss } (\text{reduce-trail-to } F S) = \text{init-clss } S$
apply (induction $F S$ rule: reduce-trail-to.induct)

by (metis init-clss-tl-trail reduce-trail-to.simps)

lemma learned-clss-update-trial[simp]:
 learned-clss (reduce-trail-to F S) = learned-clss S
 apply (induction F S rule: reduce-trail-to.induct)
 by (metis learned-clss-tl-trail reduce-trail-to.simps)

lemma trail-eq-reduce-trail-to-eq:
 trail S = trail T \implies trail (reduce-trail-to F S) = trail (reduce-trail-to F T)
 apply (induction F S arbitrary: T rule: reduce-trail-to.induct)
 by (metis trail-tl-trail reduce-trail-to.simps)

lemma reduce-trail-to-state-eq_{NOT}-compatible:
 assumes ST: $S \sim T$
 shows reduce-trail-to F S \sim reduce-trail-to F T
proof –
 have trail (reduce-trail-to F S) = trail (reduce-trail-to F T)
 using trail-eq-reduce-trail-to-eq[of S T F] ST by auto
 then show ?thesis using ST by (auto simp del: state-simp simp: state-eq-def)
qed

lemma reduce-trail-to-trail-tl-trail-decomp[simp]:
 trail S = F' @ Marked K d # F \implies (trail (reduce-trail-to F S)) = F
 apply (rule reduce-trail-to-skip-beginning[of - F' @ Marked K d # []])
 by (cases F') (auto simp add:tl-append reduce-trail-to-skip-beginning)

lemma reduce-trail-to-add-learned-clss[simp]:
 no-dup (trail S) \implies
 trail (reduce-trail-to F (add-learned-clss C S)) = trail (reduce-trail-to F S)
 by (rule trail-eq-reduce-trail-to-eq) auto

lemma reduce-trail-to-add-init-clss[simp]:
 no-dup (trail S) \implies
 trail (reduce-trail-to F (add-init-clss C S)) = trail (reduce-trail-to F S)
 by (rule trail-eq-reduce-trail-to-eq) auto

lemma reduce-trail-to-remove-learned-clss[simp]:
 trail (reduce-trail-to F (remove-clss C S)) = trail (reduce-trail-to F S)
 by (rule trail-eq-reduce-trail-to-eq) auto

lemma reduce-trail-to-update-conflicting[simp]:
 trail (reduce-trail-to F (update-conflicting C S)) = trail (reduce-trail-to F S)
 by (rule trail-eq-reduce-trail-to-eq) auto

lemma reduce-trail-to-update-backtrack-lvl[simp]:
 trail (reduce-trail-to F (update-backtrack-lvl C S)) = trail (reduce-trail-to F S)
 by (rule trail-eq-reduce-trail-to-eq) auto

lemma in-get-all-marked-decomposition-marked-or-empty:
 assumes (a, b) \in set (get-all-marked-decomposition M)
 shows a = [] \vee (is-marked (hd a))
 using assms
proof (induct M arbitrary: a b)
 case Nil then show ?case by simp
next

```

case (Cons m M)
show ?case
proof (cases m)
  case (Marked l mark)
  then show ?thesis using Cons by auto
next
  case (Propagated l mark)
  then show ?thesis using Cons by (cases get-all-marked-decomposition M) force+
qed
qed

```

```

lemma in-get-all-marked-decomposition-trail-update-trail[simp]:
  assumes H: (L # M1, M2) ∈ set (get-all-marked-decomposition (trail S))
  shows trail (reduce-trail-to M1 S) = M1
proof -
  obtain K mark where
    L: L = Marked K mark
  using H by (cases L) (auto dest!: in-get-all-marked-decomposition-marked-or-empty)
  obtain c where
    tr-S: trail S = c @ M2 @ L # M1
  using H by auto
  show ?thesis
  by (rule reduce-trail-to-trail-tl-trail-decomp[of - c @ M2 K mark])
  (auto simp: tr-S L)
qed

```

```

fun append-trail where
  append-trail [] S = S |
  append-trail (L # M) S = append-trail M (cons-trail L S)

```

```

lemma trail-append-trail[simp]:
  no-dup (M @ trail S) ⇒ trail (append-trail M S) = rev M @ trail S
  by (induction M arbitrary: S) (auto simp: defined-lit-map)

```

```

lemma learned-clss-append-trail[simp]:
  no-dup (M @ trail S) ⇒ learned-clss (append-trail M S) = learned-clss S
  by (induction M arbitrary: S) (auto simp: defined-lit-map)

```

```

lemma init-clss-append-trail[simp]:
  no-dup (M @ trail S) ⇒ init-clss (append-trail M S) = init-clss S
  by (induction M arbitrary: S) (auto simp: defined-lit-map)

```

```

lemma conflicting-append-trail[simp]:
  no-dup (M @ trail S) ⇒ conflicting (append-trail M S) = conflicting S
  by (induction M arbitrary: S) (auto simp: defined-lit-map)

```

```

lemma backtrack-lvl-append-trail[simp]:
  no-dup (M @ trail S) ⇒ backtrack-lvl (append-trail M S) = backtrack-lvl S
  by (induction M arbitrary: S) (auto simp: defined-lit-map)

```

```

lemma clauses-append-trail[simp]:
  no-dup (M @ trail S) ⇒ clauses (append-trail M S) = clauses S
  by (induction M arbitrary: S) (auto simp: defined-lit-map)

```

This function is useful for proofs to speak of a global trail change, but is a bad for programs and code in general.

```

fun delete-trail-and-rebuild where
delete-trail-and-rebuild  $M\ S = \text{append-trail } (\text{rev } M) (\text{reduce-trail-to } []\ S)$ 

end

```

17.2 Special Instantiation: using Triples as State

17.3 CDCL Rules

Because of the strategy we will later use, we distinguish propagate, conflict from the other rules

locale

```

cdclW-ops =
stateW trail init-clss learned-clss backtrack-lvl conflicting cons-trail tl-trail add-init-cls
add-learned-cls remove-cls update-backtrack-lvl update-conflicting init-state
restart-state

```

for

```

trail :: 'st  $\Rightarrow$  ('v, nat, 'v clause) marked-lits and
init-clss :: 'st  $\Rightarrow$  'v clauses and
learned-clss :: 'st  $\Rightarrow$  'v clauses and
backtrack-lvl :: 'st  $\Rightarrow$  nat and
conflicting :: 'st  $\Rightarrow$  'v clause conflicting-clause and

cons-trail :: ('v, nat, 'v clause) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
tl-trail :: 'st  $\Rightarrow$  'st and
add-init-cls :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
add-learned-cls :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
remove-cls :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
update-backtrack-lvl :: nat  $\Rightarrow$  'st  $\Rightarrow$  'st and
update-conflicting :: 'v clause conflicting-clause  $\Rightarrow$  'st  $\Rightarrow$  'st and

init-state :: 'v clauses  $\Rightarrow$  'st and
restart-state :: 'st  $\Rightarrow$  'st

```

begin

inductive propagate :: 'st \Rightarrow 'st \Rightarrow bool **where**

propagate-rule[*intro*]:

```

state  $S = (M, N, U, k, C\text{-True}) \Rightarrow C + \{\#L\# \} \in \# \text{ clauses } S \Rightarrow M \models_{as} C\text{Not } C
\Rightarrow \text{undefined-lit } (\text{trail } S) L
\Rightarrow T \sim \text{cons-trail } (\text{Propagated } L (C + \{\#L\# \})) S
\Rightarrow \text{propagate } S T$ 
```

inductive-cases propagateE[*elim*]: propagate $S\ T$

thm propagateE

inductive conflict :: 'st \Rightarrow 'st \Rightarrow bool **where**

```

conflict-rule[intro]: state  $S = (M, N, U, k, C\text{-True}) \Rightarrow D \in \# \text{ clauses } S \Rightarrow M \models_{as} C\text{Not } D
\Rightarrow T \sim \text{update-conflicting } (C\text{-Clause } D) S
\Rightarrow \text{conflict } S T$ 
```

inductive-cases conflictE[*elim*]: conflict $S\ S'$

inductive backtrack :: 'st \Rightarrow 'st \Rightarrow bool **where**

```

backtrack-rule[intro]: state  $S = (M, N, U, k, C\text{-Clause } (D + \{\#L\# \}))
\Rightarrow (\text{Marked } K (i+1) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } M)
\Rightarrow \text{get-level } L\ M = k
\Rightarrow \text{get-level } L\ M = \text{get-maximum-level } (D + \{\#L\# \}) M$ 
```

$\Rightarrow \text{get-maximum-level } D \ M = i$
 $\Rightarrow T \sim \text{cons-trail } (\text{Propagated } L \ (D + \{\#L\#}))$
 $\quad (\text{reduce-trail-to } M1$
 $\quad \quad (\text{add-learned-cls } (D + \{\#L\#}))$
 $\quad \quad (\text{update-backtrack-lvl } i$
 $\quad \quad \quad (\text{update-conflicting } C\text{-True } S)))$
 $\Rightarrow \text{backtrack } S \ T$
inductive-cases $\text{backtrackE}[\text{elim}]: \text{backtrack } S \ S'$
thm backtrackE

inductive $\text{decide} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **where**
 $\text{decide-rule}[\text{intro}]: \text{state } S = (M, N, U, k, C\text{-True})$
 $\Rightarrow \text{undefined-lit } M \ L \Rightarrow \text{atm-of } L \in \text{atms-of-msu } (\text{init-clss } S)$
 $\Rightarrow T \sim \text{cons-trail } (\text{Marked } L \ (k+1)) \ (\text{incr-lvl } S)$
 $\Rightarrow \text{decide } S \ T$
inductive-cases $\text{decideE}[\text{elim}]: \text{decide } S \ S'$
thm decideE

inductive $\text{skip} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **where**
 $\text{skip-rule}[\text{intro}]: \text{state } S = (\text{Propagated } L \ C' \ \# \ M, N, U, k, C\text{-Clause } D) \Rightarrow \neg L \notin \# \ D \Rightarrow D \neq \{\#\}$
 $\Rightarrow T \sim \text{tl-trail } S$
 $\Rightarrow \text{skip } S \ T$
inductive-cases $\text{skipE}[\text{elim}]: \text{skip } S \ S'$
thm skipE

$\text{get-maximum-level } D \ (\text{Propagated } L \ (C + \{\#L\#}) \ \# \ M) = k \vee k = 0$ is equivalent to
 $\text{get-maximum-level } D \ (\text{Propagated } L \ (C + \{\#L\#}) \ \# \ M) = k$

inductive $\text{resolve} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **where**
 $\text{resolve-rule}[\text{intro}]:$
 $\quad \text{state } S = (\text{Propagated } L \ (C + \{\#L\#})) \ \# \ M, N, U, k, C\text{-Clause } (D + \{\#-L\#}))$
 $\Rightarrow \text{get-maximum-level } D \ (\text{Propagated } L \ (C + \{\#L\#}) \ \# \ M) = k$
 $\Rightarrow T \sim \text{update-conflicting } (C\text{-Clause } (D \ \# \cup \ C)) \ (\text{tl-trail } S)$
 $\Rightarrow \text{resolve } S \ T$
inductive-cases $\text{resolveE}[\text{elim}]: \text{resolve } S \ S'$
thm resolveE

inductive $\text{restart} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **where**
 $\text{restart}: \text{state } S = (M, N, U, k, C\text{-True}) \Rightarrow \neg M \models \text{asm clauses } S$
 $\Rightarrow T \sim \text{restart-state } S$
 $\Rightarrow \text{restart } S \ T$
inductive-cases $\text{restartE}[\text{elim}]: \text{restart } S \ T$
thm restartE

We add the condition $C \notin \# \text{init-clss } S$, to maintain consistency even without the strategy.

inductive $\text{forget} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **where**
 $\text{forget-rule}: \text{state } S = (M, N, \{\#C\# \} + U, k, C\text{-True})$
 $\Rightarrow \neg M \models \text{asm clauses } S$
 $\Rightarrow C \notin \text{set } (\text{get-all-mark-of-propagated } (\text{trail } S))$
 $\Rightarrow C \notin \# \text{init-clss } S$
 $\Rightarrow C \in \# \text{learned-clss } S$
 $\Rightarrow T \sim \text{remove-cls } C \ S$
 $\Rightarrow \text{forget } S \ T$
inductive-cases $\text{forgetE}[\text{elim}]: \text{forget } S \ T$

inductive $\text{cdcl}_W\text{-rf} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **for** $S :: 'st$ **where**

restart: $\text{restart } S \ T \Longrightarrow \text{cdcl}_W\text{-rf } S \ T \mid$
forget: $\text{forget } S \ T \Longrightarrow \text{cdcl}_W\text{-rf } S \ T$

inductive $\text{cdcl}_W\text{-bj} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **where**
skip[intro]: $\text{skip } S \ S' \Longrightarrow \text{cdcl}_W\text{-bj } S \ S' \mid$
resolve[intro]: $\text{resolve } S \ S' \Longrightarrow \text{cdcl}_W\text{-bj } S \ S' \mid$
backtrack[intro]: $\text{backtrack } S \ S' \Longrightarrow \text{cdcl}_W\text{-bj } S \ S'$

inductive-cases $\text{cdcl}_W\text{-bjE}$: $\text{cdcl}_W\text{-bj } S \ T$

inductive $\text{cdcl}_W\text{-o} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **for** $S :: 'st$ **where**
decide[intro]: $\text{decide } S \ S' \Longrightarrow \text{cdcl}_W\text{-o } S \ S' \mid$
bj[intro]: $\text{cdcl}_W\text{-bj } S \ S' \Longrightarrow \text{cdcl}_W\text{-o } S \ S'$

inductive $\text{cdcl}_W :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **for** $S :: 'st$ **where**
propagate: $\text{propagate } S \ S' \Longrightarrow \text{cdcl}_W \ S \ S' \mid$
conflict: $\text{conflict } S \ S' \Longrightarrow \text{cdcl}_W \ S \ S' \mid$
other: $\text{cdcl}_W\text{-o } S \ S' \Longrightarrow \text{cdcl}_W \ S \ S' \mid$
rf: $\text{cdcl}_W\text{-rf } S \ S' \Longrightarrow \text{cdcl}_W \ S \ S'$

lemma *rtrancpl-propagate-is-rtrancpl-cdcl_W*:
 $\text{propagate}^{**} \ S \ S' \Longrightarrow \text{cdcl}_W^{**} \ S \ S'$
by (induction rule: *rtrancpl-induct*) (*fastforce dest!*: *propagate*)**+**

lemma *cdcl_W-all-rules-induct*[*consumes 1, case-names propagate conflict forget restart decide skip resolve backtrack*]:

fixes $S :: 'st$
assumes
 cdcl_W : $\text{cdcl}_W \ S \ S'$ **and**
propagate: $\bigwedge T. \text{propagate } S \ T \Longrightarrow P \ S \ T$ **and**
conflict: $\bigwedge T. \text{conflict } S \ T \Longrightarrow P \ S \ T$ **and**
forget: $\bigwedge T. \text{forget } S \ T \Longrightarrow P \ S \ T$ **and**
restart: $\bigwedge T. \text{restart } S \ T \Longrightarrow P \ S \ T$ **and**
decide: $\bigwedge T. \text{decide } S \ T \Longrightarrow P \ S \ T$ **and**
skip: $\bigwedge T. \text{skip } S \ T \Longrightarrow P \ S \ T$ **and**
resolve: $\bigwedge T. \text{resolve } S \ T \Longrightarrow P \ S \ T$ **and**
backtrack: $\bigwedge T. \text{backtrack } S \ T \Longrightarrow P \ S \ T$
shows $P \ S \ S'$

using *assms*(1)
proof (*induct S' rule: cdcl_W.induct*)
case (*propagate S'*) **note** *propagate = this*(1)
then show ?*case* **using** *assms*(2) **by** *auto*
next
case (*conflict S'*)
then show ?*case* **using** *assms*(3) **by** *auto*
next
case (*other S'*)
then show ?*case*
proof (*induct rule: cdcl_W-o.induct*)
case (*decide U*)
then show ?*case* **using** *assms*(6) **by** *auto*
next
case (*bj S'*)
then show ?*case* **using** *assms*(7–9) **by** (*induction rule: cdcl_W-bj.induct*) *auto*
qed

next
case (*rf S'*)
then show ?*case*
by (*induct rule: cdcl_W-rf.induct*) (*fast dest: forget restart*)+
qed

lemma *cdcl_W-all-induct*[*consumes 1, case-names propagate conflict forget restart decide skip resolve backtrack*]:

fixes *S* :: 'st

assumes

cdcl_W: *cdcl_W S S'* **and**

propagateH: $\bigwedge C L T. C + \{\#L\# \} \in \# \text{ clauses } S \implies \text{trail } S \models_{as} C \text{Not } C$

$\implies \text{undefined-lit } (\text{trail } S) L \implies \text{conflicting } S = C\text{-True}$

$\implies T \sim \text{cons-trail } (\text{Propagated } L (C + \{\#L\# \})) S$

$\implies P S T$ **and**

conflictH: $\bigwedge D T. D \in \# \text{ clauses } S \implies \text{conflicting } S = C\text{-True} \implies \text{trail } S \models_{as} C \text{Not } D$

$\implies T \sim \text{update-conflicting } (C\text{-Clause } D) S$

$\implies P S T$ **and**

forgetH: $\bigwedge C T. \neg \text{trail } S \models_{asm} \text{clauses } S$

$\implies C \notin \text{set } (\text{get-all-mark-of-propagated } (\text{trail } S))$

$\implies C \notin \# \text{ init-clss } S$

$\implies C \in \# \text{ learned-clss } S$

$\implies \text{conflicting } S = C\text{-True}$

$\implies T \sim \text{remove-cl } C S$

$\implies P S T$ **and**

restartH: $\bigwedge T. \neg \text{trail } S \models_{asm} \text{clauses } S$

$\implies \text{conflicting } S = C\text{-True}$

$\implies T \sim \text{restart-state } S$

$\implies P S T$ **and**

decideH: $\bigwedge L T. \text{conflicting } S = C\text{-True} \implies \text{undefined-lit } (\text{trail } S) L$

$\implies \text{atm-of } L \in \text{atms-of-msu } (\text{init-clss } S)$

$\implies T \sim \text{cons-trail } (\text{Marked } L (\text{backtrack-lvl } S + 1)) (\text{incr-lvl } S)$

$\implies P S T$ **and**

skipH: $\bigwedge L C' M D T. \text{trail } S = \text{Propagated } L C' \# M$

$\implies \text{conflicting } S = C\text{-Clause } D \implies \neg L \notin \# D \implies D \neq \{\#\}$

$\implies T \sim \text{tl-trail } S$

$\implies P S T$ **and**

resolveH: $\bigwedge L C M D T.$

$\text{trail } S = \text{Propagated } L ((C + \{\#L\# \})) \# M$

$\implies \text{conflicting } S = C\text{-Clause } (D + \{\#-L\# \})$

$\implies \text{get-maximum-level } D (\text{Propagated } L ((C + \{\#L\# \})) \# M) = \text{backtrack-lvl } S$

$\implies T \sim (\text{update-conflicting } (C\text{-Clause } (D \# \cup C)) (\text{tl-trail } S))$

$\implies P S T$ **and**

backtrackH: $\bigwedge K i M1 M2 L D T.$

$(\text{Marked } K (\text{Suc } i) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$

$\implies \text{get-level } L (\text{trail } S) = \text{backtrack-lvl } S$

$\implies \text{conflicting } S = C\text{-Clause } (D + \{\#L\# \})$

$\implies \text{get-maximum-level } (D + \{\#L\# \}) (\text{trail } S) = \text{get-level } L (\text{trail } S)$

$\implies \text{get-maximum-level } D (\text{trail } S) \equiv i$

$\implies T \sim \text{cons-trail } (\text{Propagated } L (D + \{\#L\# \}))$

$(\text{reduce-trail-to } M1$

$(\text{add-learned-cl } (D + \{\#L\# \})$

$(\text{update-backtrack-lvl } i$

$(\text{update-conflicting } C\text{-True } S))))$

$\implies P S T$

```

shows  $P S S'$ 
using  $cdcl_W$ 
proof (induct  $S S'$  rule:  $cdcl_W$ -all-rules-induct)
  case (propagate  $S'$ )
  then show ?case by (elim propagateE) (frule propagateH; simp)
next
  case (conflict  $S'$ )
  then show ?case by (elim conflictE) (frule conflictH; simp)
next
  case (restart  $S'$ )
  then show ?case by (elim restartE) (frule restartH; simp)
next
  case (decide  $T$ )
  then show ?case by (elim decideE) (frule decideH; simp)
next
  case (backtrack  $S'$ )
  then show ?case by (elim backtrackE) (frule backtrackH; simp del: state-simp add: state-eq-def)
next
  case (forget  $S'$ )
  then show ?case using forgetH by auto
next
  case (skip  $S'$ )
  then show ?case using skipH by auto
next
  case (resolve  $S'$ )
  then show ?case by (elim resolveE) (frule resolveH; simp)
qed

```

lemma $cdcl_W$ -o-induct[consumes 1, case-names decide skip resolve backtrack]:

fixes $S :: 'st$

assumes $cdcl_W$: $cdcl_W$ -o $S T$ **and**

$decideH$: $\bigwedge L T. \text{conflicting } S = C\text{-True} \implies \text{undefined-lit } (\text{trail } S) L$
 $\implies \text{atm-of } L \in \text{atms-of-msu } (\text{init-clss } S)$
 $\implies T \sim \text{cons-trail } (\text{Marked } L (\text{backtrack-lvl } S + 1)) (\text{incr-lvl } S)$
 $\implies P S T$ **and**

$skipH$: $\bigwedge L C' M D T. \text{trail } S = \text{Propagated } L C' \# M$
 $\implies \text{conflicting } S = C\text{-Clause } D \implies -L \notin \# D \implies D \neq \{\#\}$
 $\implies T \sim \text{tl-trail } S$
 $\implies P S T$ **and**

$resolveH$: $\bigwedge L C M D T.$
 $\text{trail } S = \text{Propagated } L ((C + \{\#L\# \}) \# M$
 $\implies \text{conflicting } S = C\text{-Clause } (D + \{\#-L\# \})$
 $\implies \text{get-maximum-level } D (\text{Propagated } L (C + \{\#L\# \}) \# M) = \text{backtrack-lvl } S$
 $\implies T \sim \text{update-conflicting } (C\text{-Clause } (D \# \cup C)) (\text{tl-trail } S)$
 $\implies P S T$ **and**

$backtrackH$: $\bigwedge K i M1 M2 L D T.$
 $(\text{Marked } K (\text{Suc } i) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$
 $\implies \text{get-level } L (\text{trail } S) = \text{backtrack-lvl } S$
 $\implies \text{conflicting } S = C\text{-Clause } (D + \{\#L\# \})$
 $\implies \text{get-level } L (\text{trail } S) = \text{get-maximum-level } (D + \{\#L\# \}) (\text{trail } S)$
 $\implies \text{get-maximum-level } D (\text{trail } S) \equiv i$
 $\implies T \sim \text{cons-trail } (\text{Propagated } L (D + \{\#L\# \}))$
 $\quad (\text{reduce-trail-to } M1$
 $\quad \quad (\text{add-learned-cls } (D + \{\#L\# \}))$
 $\quad \quad (\text{update-backtrack-lvl } i$

```

      (update-conflicting C-True S))))
    => P S T
  shows P S T
  using cdclW-o-induct (induct T rule: cdclW-o.induct)
    using assms(2) apply auto[1]
  apply (elim cdclW-bjE skipE resolveE backtrackE)
    apply (frule skipH; simp)
    apply (frule resolveH; simp)
  apply (frule backtrackH; simp-all del: state-simp add: state-eq-def)
  done

thm cdclW-o-induct
lemma cdclW-o-all-rules-induct[consumes 1, case-names decide backtrack skip resolve]:
  fixes S T :: 'st
  assumes
    cdclW-o S T and
     $\bigwedge T. \text{decide } S \ T \implies P \ S \ T$  and
     $\bigwedge T. \text{backtrack } S \ T \implies P \ S \ T$  and
     $\bigwedge T. \text{skip } S \ T \implies P \ S \ T$  and
     $\bigwedge T. \text{resolve } S \ T \implies P \ S \ T$ 
  shows P S T
  using assms by (induct T rule: cdclW-o.induct) (auto simp: cdclW-bj.simps)

lemma cdclW-o-rule-cases[consumes 1, case-names decide backtrack skip resolve]:
  fixes S T :: 'st
  assumes
    cdclW-o S T and
    decide S T  $\implies$  P and
    backtrack S T  $\implies$  P and
    skip S T  $\implies$  P and
    resolve S T  $\implies$  P
  shows P
  using assms by (auto simp: cdclW-o.simps cdclW-bj.simps)

```

17.4 Invariants

17.4.1 Properties of the trail

We here establish that: * the marks are exactly 1..k where k is the level * the consistency of the trail * the fact that there is no duplicate in the trail.

```

lemma backtrack-lit-skipped:
  assumes L: get-level L (trail S) = backtrack-lvl S
  and M1: (Marked K (i + 1) # M1, M2) ∈ set (get-all-marked-decomposition (trail S))
  and no-dup: no-dup (trail S)
  and bt-l: backtrack-lvl S = length (get-all-levels-of-marked (trail S))
  and order: get-all-levels-of-marked (trail S)
    = rev ([1.. $(1 + \text{length (get-all-levels-of-marked (trail S))})$ ])
  shows atm-of L  $\notin$  atm-of ' lits-of M1
proof
  let ?M = trail S
  assume L-in-M1: atm-of L ∈ atm-of ' lits-of M1
  obtain c where Mc: trail S = c @ M2 @ Marked K (i + 1) # M1 using M1 by blast
  have atm-of L  $\notin$  atm-of ' lits-of c
    using L-in-M1 no-dup mk-disjoint-insert unfolding Mc lits-of-def by force
  have g-M-eq-g-M1: get-level L ?M = get-level L M1

```

using L -in- $M1$ unfolding Mc by *auto*
 have g : $\text{get-all-levels-of-marked } M1 = \text{rev } [1..<\text{Suc } i]$
 using *order* unfolding Mc
 by (*auto* *simp* *del*: *upt-simps* *dest*!: *append-cons-eq-upt-length-i*
 simp *add*: *rev-swap*[*symmetric*])
 then have $\text{Max } (\text{set } (0 \# \text{get-all-levels-of-marked } (\text{rev } M1))) < \text{Suc } i$ by *auto*
 then have $\text{get-level } L \ M1 < \text{Suc } i$
 using $\text{get-rev-level-less-max-get-all-levels-of-marked}[of \ L \ 0 \ \text{rev } M1]$ by *linarith*
 moreover have $\text{Suc } i \leq \text{backtrack-lvl } S$ using *bt-l* by (*simp* *add*: $Mc \ g$)
 ultimately show *False* using $L \ g$ - M - eq - g - $M1$ by *auto*
 qed

lemma $cdcl_W$ -distinctinv-1:

assumes
 $cdcl_W \ S \ S'$ and
 $\text{no-dup } (\text{trail } S)$ and
 $\text{backtrack-lvl } S = \text{length } (\text{get-all-levels-of-marked } (\text{trail } S))$ and
 $\text{get-all-levels-of-marked } (\text{trail } S) = \text{rev } [1..<1+\text{length } (\text{get-all-levels-of-marked } (\text{trail } S))]$
 shows $\text{no-dup } (\text{trail } S')$
 using *assms*
proof (*induct* rule: $cdcl_W$ -all-induct)
 case ($\text{backtrack } K \ i \ M1 \ M2 \ L \ D \ T$) **note** $\text{decomp} = \text{this}(1)$ and $L = \text{this}(2)$ and $T = \text{this}(6)$ and
 $n-d = \text{this}(7)$
 obtain c where Mc : $\text{trail } S = c @ M2 @ \text{Marked } K \ (i + 1) \ \# \ M1$
 using *decomp* by *auto*
 have $\text{no-dup } (M2 @ \text{Marked } K \ (i + 1) \ \# \ M1)$
 using $Mc \ n-d$ by *fastforce*
 moreover have $\text{atm-of } L \notin (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ 'set } M1$
 using $\text{backtrack-lit-skipped}[of \ L \ S \ K \ i \ M1 \ M2] \ L \ \text{decomp} \ \text{backtrack.prem}$
 by (*fastforce* *simp* *add*: *lits-of-def*)
 moreover then have $\text{undefined-lit } M1 \ L$
 by (*simp* *add*: *defined-lit-map*)
 ultimately show *?case* using *decomp* $T \ n-d$ by *simp*
 qed (*auto* *simp* *add*: *defined-lit-map*)

lemma $cdcl_W$ -consistent-inv-2:

assumes
 $cdcl_W \ S \ S'$ and
 $\text{no-dup } (\text{trail } S)$ and
 $\text{backtrack-lvl } S = \text{length } (\text{get-all-levels-of-marked } (\text{trail } S))$ and
 $\text{get-all-levels-of-marked } (\text{trail } S) = \text{rev } [1..<1+\text{length } (\text{get-all-levels-of-marked } (\text{trail } S))]$
 shows $\text{consistent-interp } (\text{lits-of } (\text{trail } S'))$
 using $cdcl_W$ -distinctinv-1 [*OF* *assms*] *distinctconsistent-interp* by *fast*

lemma $cdcl_W$ -o-bt:

assumes
 $cdcl_W$ -o $S \ S'$ and
 $\text{backtrack-lvl } S = \text{length } (\text{get-all-levels-of-marked } (\text{trail } S))$ and
 $\text{get-all-levels-of-marked } (\text{trail } S) =$
 $\text{rev } ([1..<(1+\text{length } (\text{get-all-levels-of-marked } (\text{trail } S)))])$ and
 $n-d[\text{simp}]: \text{no-dup } (\text{trail } S)$
 shows $\text{backtrack-lvl } S' = \text{length } (\text{get-all-levels-of-marked } (\text{trail } S'))$
 using *assms*
proof (*induct* rule: $cdcl_W$ -o-induct)
 case ($\text{backtrack } K \ i \ M1 \ M2 \ L \ D \ T$) **note** $\text{decomp} = \text{this}(1)$ and $T = \text{this}(6)$ and $\text{level} = \text{this}(8)$

```

have [simp]: trail (reduce-trail-to M1 S) = M1
  using decomp by auto
obtain c where M: trail S = c @ M2 @ Marked K (i + 1) # M1 using decomp by auto
have rev (get-all-levels-of-marked (trail S))
  = [1..l + (length (get-all-levels-of-marked (trail S)))]
  using level by (auto simp: rev-swap[symmetric])
moreover have atm-of L  $\notin$  ( $\lambda l$ . atm-of (lit-of l)) ‘ set M1
  using backtrack-lit-skipped[of L S K i M1 M2] backtrack(2,7,8,9) decomp
  by (fastforce simp add: lits-of-def)
moreover then have undefined-lit M1 L
  by (simp add: defined-lit-map)
moreover then have no-dup (trail T)
  using T decomp n-d by (auto simp: defined-lit-map M)
ultimately show ?case
  using T n-d unfolding M by (auto dest!: append-cons-eq-upt-length simp del: upt-simps)
qed auto

```

```

lemma cdclW-rf-bt:
  assumes
    cdclW-rf S S' and
    backtrack-lvl S = length (get-all-levels-of-marked (trail S)) and
    get-all-levels-of-marked (trail S) = rev [1..l + (length (get-all-levels-of-marked (trail S)))]
  shows backtrack-lvl S' = length (get-all-levels-of-marked (trail S'))
  using assms by (induct rule: cdclW-rf.induct) auto

```

```

lemma cdclW-bt:
  assumes
    cdclW S S' and
    backtrack-lvl S = length (get-all-levels-of-marked (trail S)) and
    get-all-levels-of-marked (trail S)
    = rev ([1..l + (length (get-all-levels-of-marked (trail S)))] and
    no-dup (trail S)
  shows backtrack-lvl S' = length (get-all-levels-of-marked (trail S'))
  using assms by (induct rule: cdclW.induct) (auto simp add: cdclW-o-bt cdclW-rf-bt)

```

```

lemma cdclW-bt-level':
  assumes
    cdclW S S' and
    backtrack-lvl S = length (get-all-levels-of-marked (trail S)) and
    get-all-levels-of-marked (trail S)
    = rev ([1..l + (length (get-all-levels-of-marked (trail S)))] and
    n-d: no-dup (trail S)
  shows get-all-levels-of-marked (trail S')
    = rev ([1..l + (length (get-all-levels-of-marked (trail S')))] and
  using assms
proof (induct rule: cdclW-all-induct)
  case (decide L T) note undef = this(2) and T = this(4)
  let ?k = backtrack-lvl S
  let ?M = trail S
  let ?M' = Marked L (?k + 1) # trail S
  have H: get-all-levels-of-marked ?M = rev [Suc 0..l + (length (get-all-levels-of-marked ?M))]
    using decide.premis by simp
  have k: ?k = length (get-all-levels-of-marked ?M)
    using decide.premis by auto
  have get-all-levels-of-marked ?M' = Suc ?k # get-all-levels-of-marked ?M by simp

```

```

then have get-all-levels-of-marked ?M' = Suc ?k #
  rev [Suc 0..1+length (get-all-levels-of-marked ?M)]
using H by auto
moreover have ... = rev [Suc 0..Suc (1+length (get-all-levels-of-marked ?M))]
  unfolding k by simp
finally show ?case using T undef by (auto simp add: defined-lit-map)
next
  case (backtrack K i M1 M2 L D T) note decomp = this(1) and confli = this(2) and T = this(6)
and
  all-marked = this(8) and bt-lvl = this(7)
have atm-of L  $\notin$  ( $\lambda l. \text{atm-of } (\text{lit-of } l)$ ) ‘ set M1
  using backtrack-lit-skipped[of L S K i M1 M2] backtrack(2,7,8,9) decomp
  by (fastforce simp add: lits-of-def)
moreover then have undefined-lit M1 L
  by (simp add: defined-lit-map)
then have [simp]: trail T = Propagated L (D + {#L#}) # M1
  using T decomp n-d by auto
obtain c where M: trail S = c @ M2 @ Marked K (i + 1) # M1 using decomp by auto
have get-all-levels-of-marked (rev (trail S))
  = [Suc 0..2+length (get-all-levels-of-marked c) + (length (get-all-levels-of-marked M2)
    + length (get-all-levels-of-marked M1))]
  using all-marked bt-lvl unfolding M by (auto simp add: rev-swap[symmetric] simp del: upt-simps)
then show ?case
  using T by (auto simp add: rev-swap M dest!: append-cons-eq-upt(1) simp del: upt-simps)
qed auto

```

We write $1 + \text{length } (\text{get-all-levels-of-marked } (\text{trail } S))$ instead of *backtrack-lvl* *S* to avoid non termination of rewriting.

definition *cdcl_W-M-level-inv* (*S*:: 'st) \longleftrightarrow
consistent-interp (*lits-of* (*trail* *S*))
 \wedge *no-dup* (*trail* *S*)
 \wedge *backtrack-lvl* *S* = *length* (*get-all-levels-of-marked* (*trail* *S*))
 \wedge *get-all-levels-of-marked* (*trail* *S*)
 = *rev* ([1..*1+length* (*get-all-levels-of-marked* (*trail* *S*))])

lemma *cdcl_W-M-level-inv-decomp*:
assumes *cdcl_W-M-level-inv* *S*
shows *consistent-interp* (*lits-of* (*trail* *S*))
and *no-dup* (*trail* *S*)
using *assms* **unfolding** *cdcl_W-M-level-inv-def* **by** *fastforce*+

lemma *cdcl_W-consistent-inv*:
fixes *S S'* :: 'st
assumes
cdcl_W *S S'* **and**
cdcl_W-M-level-inv *S*
shows *cdcl_W-M-level-inv* *S'*
using *assms cdcl_W-consistent-inv-2 cdcl_W-distinctinv-1 cdcl_W-bt cdcl_W-bt-level'*
unfolding *cdcl_W-M-level-inv-def* **by** *meson*+

lemma *rtrancpl-cdcl_W-consistent-inv*:
assumes *cdcl_W*** *S S'*
and *cdcl_W-M-level-inv* *S*
shows *cdcl_W-M-level-inv* *S'*
using *assms* **by** (*induct rule: rtrancpl-induct*)

(auto intro: cdcl_W-consistent-inv)

lemma *trancpl-cdcl_W-consistent-inv*:
assumes *cdcl_W⁺⁺ S S'*
and *cdcl_W-M-level-inv S*
shows *cdcl_W-M-level-inv S'*
using *assms* **by** (*induct rule: trancpl-induct*)
(auto intro: cdcl_W-consistent-inv)

lemma *cdcl_W-M-level-inv-S0-cdcl_W[simp]*:
cdcl_W-M-level-inv (init-state N)
unfolding *cdcl_W-M-level-inv-def* **by** *auto*

lemma *cdcl_W-M-level-inv-get-level-le-backtrack-lvl*:
assumes *inv: cdcl_W-M-level-inv S*
shows *get-level L (trail S) ≤ backtrack-lvl S*

proof –
have *get-all-levels-of-marked (trail S) = rev [1..₁ + backtrack-lvl S]*
using *inv* **unfolding** *cdcl_W-M-level-inv-def* **by** *auto*
then show *?thesis*
using *get-rev-level-less-max-get-all-levels-of-marked[of L 0 rev (trail S)]*
by (*auto simp: Max-n-upt*)
qed

lemma *backtrack-ex-decomp*:
assumes *M-l: cdcl_W-M-level-inv S*
and *i-S: i < backtrack-lvl S*
shows $\exists K M1 M2. (\text{Marked } K (i + 1) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$

proof –
let *?M = trail S*
have
g: get-all-levels-of-marked (trail S) = rev [Suc 0..₁ Suc (backtrack-lvl S)]
using *M-l* **unfolding** *cdcl_W-M-level-inv-def* **by** *simp-all*
then have $i+1 \in \text{set } (\text{get-all-levels-of-marked } (\text{trail } S))$
using *i-S* **by** *auto*

then obtain *c K c'* **where** *tr-S: trail S = c @ Marked K (i + 1) # c'*
using *in-get-all-levels-of-marked-iff-decomp[of i+1 trail S]* **by** *auto*

obtain *M1 M2* **where** $(\text{Marked } K (i + 1) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$
unfolding *tr-S* **apply** (*induct c rule: marked-lit-list-induct*)
apply *auto[2]*
apply (*case-tac hd (get-all-marked-decomposition (xs @ Marked K (Suc i) # c'))*)
apply (*case-tac get-all-marked-decomposition (xs @ Marked K (Suc i) # c')*)
by *auto*
then show *?thesis* **by** *blast*
qed

17.4.2 Better-Suited Induction Principle

Ew generalise the induction principle defined previously: the induction case for *backtrack* now includes the assumption that *undefined-lit M1 L*. This helps the simplifier and thus the automation.

lemma *backtrack-induction-lev[consumes 1, case-names M-devel-inv backtrack]*:
assumes

bt: backtrack S T **and**
inv: $cdcl_W$ - M -level-inv S **and**
backtrackH: $\bigwedge K$ i $M1$ $M2$ L D T .
 $(\text{Marked } K (\text{Suc } i) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$
 $\implies \text{get-level } L (\text{trail } S) = \text{backtrack-lvl } S$
 $\implies \text{conflicting } S = C\text{-Clause } (D + \{\#L\# \})$
 $\implies \text{get-level } L (\text{trail } S) = \text{get-maximum-level } (D + \{\#L\# \}) (\text{trail } S)$
 $\implies \text{get-maximum-level } D (\text{trail } S) \equiv i$
 $\implies \text{undefined-lit } M1$ L
 $\implies T \sim \text{cons-trail } (\text{Propagated } L (D + \{\#L\# \}))$
 $(\text{reduce-trail-to } M1$
 $(\text{add-learned-cls } (D + \{\#L\# \}))$
 $(\text{update-backtrack-lvl } i$
 $(\text{update-conflicting } C\text{-True } S))))$
 $\implies P$ S T
shows P S T
proof –
obtain K i $M1$ $M2$ L D **where**
 $\text{decomp: } (\text{Marked } K (\text{Suc } i) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$ **and**
 L : $\text{get-level } L (\text{trail } S) = \text{backtrack-lvl } S$ **and**
 $\text{confl: } \text{conflicting } S = C\text{-Clause } (D + \{\#L\# \})$ **and**
 $\text{lev-L: } \text{get-level } L (\text{trail } S) = \text{get-maximum-level } (D + \{\#L\# \}) (\text{trail } S)$ **and**
 $\text{lev-D: } \text{get-maximum-level } D (\text{trail } S) \equiv i$ **and**
 T : $T \sim \text{cons-trail } (\text{Propagated } L (D + \{\#L\# \}))$
 $(\text{reduce-trail-to } M1$
 $(\text{add-learned-cls } (D + \{\#L\# \}))$
 $(\text{update-backtrack-lvl } i$
 $(\text{update-conflicting } C\text{-True } S))))$
using bt **by** (elim backtrackE) *metis*

have $\text{atm-of } L \notin (\lambda l. \text{atm-of } (\text{lit-of } l))$ ‘ $\text{set } M1$
using $\text{backtrack-lit-skipped}[\text{of } L$ S K i $M1$ $M2]$ L decomp bt confl lev-L lev-D inv
unfolding $cdcl_W$ - M -level-inv-def
by $(\text{fastforce simp add: lits-of-def})$
then have $\text{undefined-lit } M1$ L
by $(\text{auto simp: defined-lit-map})$
then show $?thesis$
using $\text{backtrackH}[\text{OF } \text{decomp } L$ confl lev-L lev-D $- T]$ **by** simp
qed

lemmas $\text{backtrack-induction-lev2} = \text{backtrack-induction-lev}[\text{consumes } 2, \text{case-names backtrack}]$

lemma $cdcl_W$ -all-induct-lev-full:

fixes S :: ‘ st

assumes

$cdcl_W$: $cdcl_W$ S S' **and**

$\text{inv}[\text{simp}]$: $cdcl_W$ - M -level-inv S **and**

$\text{propagateH: } \bigwedge C$ L T . $C + \{\#L\# \} \in \# \text{ clauses } S \implies \text{trail } S \models_{as} C\text{Not } C$

$\implies \text{undefined-lit } (\text{trail } S)$ $L \implies \text{conflicting } S = C\text{-True}$

$\implies T \sim \text{cons-trail } (\text{Propagated } L (C + \{\#L\# \}))$ S

$\implies cdcl_W$ - M -level-inv S

$\implies P$ S T **and**

$\text{conflictH: } \bigwedge D$ T . $D \in \# \text{ clauses } S \implies \text{conflicting } S = C\text{-True} \implies \text{trail } S \models_{as} C\text{Not } D$

$\implies T \sim \text{update-conflicting } (C\text{-Clause } D)$ S

$\implies P$ S T **and**

$forgetH: \bigwedge C T. \neg trail\ S \models_{asm} clauses\ S$
 $\implies C \notin set\ (get-all-mark-of-propagated\ (trail\ S))$
 $\implies C \notin \# init-clss\ S$
 $\implies C \in \# learned-clss\ S$
 $\implies conflicting\ S = C-True$
 $\implies T \sim remove-cl\ C\ S$
 $\implies cdcl_W-M-level-inv\ S$
 $\implies P\ S\ T\ \mathbf{and}$
 $restartH: \bigwedge T. \neg trail\ S \models_{asm} clauses\ S$
 $\implies conflicting\ S = C-True$
 $\implies T \sim restart-state\ S$
 $\implies cdcl_W-M-level-inv\ S$
 $\implies P\ S\ T\ \mathbf{and}$
 $decideH: \bigwedge L T. conflicting\ S = C-True \implies undefined-lit\ (trail\ S)\ L$
 $\implies atm-of\ L \in atms-of-msu\ (init-clss\ S)$
 $\implies T \sim cons-trail\ (Marked\ L\ (backtrack-lvl\ S + 1))\ (incr-lvl\ S)$
 $\implies cdcl_W-M-level-inv\ S$
 $\implies P\ S\ T\ \mathbf{and}$
 $skipH: \bigwedge L C' M D T. trail\ S = Propagated\ L\ C' \# M$
 $\implies conflicting\ S = C-Clause\ D \implies -L \notin \# D \implies D \neq \{\#\}$
 $\implies T \sim tl-trail\ S$
 $\implies cdcl_W-M-level-inv\ S$
 $\implies P\ S\ T\ \mathbf{and}$
 $resolveH: \bigwedge L C M D T.$
 $trail\ S = Propagated\ L\ ((C + \{\#L\#})) \# M$
 $\implies conflicting\ S = C-Clause\ (D + \{\#-L\#})$
 $\implies get-maximum-level\ D\ (Propagated\ L\ ((C + \{\#L\#})) \# M) = backtrack-lvl\ S$
 $\implies T \sim (update-conflicting\ (C-Clause\ (D \# \cup C))\ (tl-trail\ S))$
 $\implies cdcl_W-M-level-inv\ S$
 $\implies P\ S\ T\ \mathbf{and}$
 $backtrackH: \bigwedge K i M1 M2 L D T.$
 $(Marked\ K\ (Suc\ i) \# M1, M2) \in set\ (get-all-marked-decomposition\ (trail\ S))$
 $\implies get-level\ L\ (trail\ S) = backtrack-lvl\ S$
 $\implies conflicting\ S = C-Clause\ (D + \{\#L\#})$
 $\implies get-maximum-level\ (D + \{\#L\#})\ (trail\ S) = get-level\ L\ (trail\ S)$
 $\implies get-maximum-level\ D\ (trail\ S) \equiv i$
 $\implies undefined-lit\ M1\ L$
 $\implies T \sim cons-trail\ (Propagated\ L\ (D + \{\#L\#}))$
 $\quad (reduce-trail-to\ M1$
 $\quad \quad (add-learned-cl\ (D + \{\#L\#})$
 $\quad \quad \quad (update-backtrack-lvl\ i$
 $\quad \quad \quad \quad (update-conflicting\ C-True\ S))))$
 $\implies cdcl_W-M-level-inv\ S$
 $\implies P\ S\ T$
 $\mathbf{shows}\ P\ S\ S'$
 $\mathbf{using}\ cdcl_W$
 $\mathbf{proof}\ (induct\ S'\ \text{rule: } cdcl_W\text{-all-rules-induct})$
 $\mathbf{case}\ (propagate\ S')$
 $\mathbf{then\ show}\ ?case\ \mathbf{by}\ (elim\ propagateE)\ (frule\ propagateH; simp)$
 \mathbf{next}
 $\mathbf{case}\ (conflict\ S')$
 $\mathbf{then\ show}\ ?case\ \mathbf{by}\ (elim\ conflictE)\ (frule\ conflictH; simp)$
 \mathbf{next}
 $\mathbf{case}\ (restart\ S')$
 $\mathbf{then\ show}\ ?case\ \mathbf{by}\ (elim\ restartE)\ (frule\ restartH; simp)$

```

next
  case (decide T)
  then show ?case by (elim decideE) (frule decideH; simp)
next
  case (backtrack S')
  then show ?case
    apply (induction rule: backtrack-induction-lev)
    apply (rule inv)
    by (rule backtrackH;
        fastforce simp del: state-simp simp add: state-eq-def dest!: HOL.meta-eq-to-obj-eq)
next
  case (forget S')
  then show ?case using forgetH by auto
next
  case (skip S')
  then show ?case using skipH by auto
next
  case (resolve S')
  then show ?case by (elim resolveE) (frule resolveH; simp)
qed

lemmas cdclW-all-induct-lev2 = cdclW-all-induct-lev-full[consumes 2, case-names propagate conflict
forget restart decide skip resolve backtrack]

lemmas cdclW-all-induct-lev = cdclW-all-induct-lev-full[consumes 1, case-names lev-inv propagate
conflict forget restart decide skip resolve backtrack]

thm cdclW-o-induct
lemma cdclW-o-induct-lev[consumes 1, case-names M-lev decide skip resolve backtrack]:
  fixes S :: 'st
  assumes
    cdclW: cdclW-o S T and
    inv[simp]: cdclW-M-level-inv S and
    decideH:  $\bigwedge L T. \text{conflicting } S = C\text{-True} \implies \text{undefined-lit } (\text{trail } S) L$ 
       $\implies \text{atm-of } L \in \text{atms-of-msu } (\text{init-clss } S)$ 
       $\implies T \sim \text{cons-trail } (\text{Marked } L (\text{backtrack-lvl } S + 1)) (\text{incr-lvl } S)$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    skipH:  $\bigwedge L C' M D T. \text{trail } S = \text{Propagated } L C' \# M$ 
       $\implies \text{conflicting } S = C\text{-Clause } D \implies -L \notin \# D \implies D \neq \{\#\}$ 
       $\implies T \sim \text{tl-trail } S$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    resolveH:  $\bigwedge L C M D T.$ 
       $\text{trail } S = \text{Propagated } L ( (C + \{\#L\# \}) \# M$ 
       $\implies \text{conflicting } S = C\text{-Clause } (D + \{\#-L\# \})$ 
       $\implies \text{get-maximum-level } D (\text{Propagated } L (C + \{\#L\# \}) \# M) = \text{backtrack-lvl } S$ 
       $\implies T \sim \text{update-conflicting } (C\text{-Clause } (D \# \cup C)) (\text{tl-trail } S)$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    backtrackH:  $\bigwedge K i M1 M2 L D T.$ 
       $(\text{Marked } K (\text{Suc } i) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$ 
       $\implies \text{get-level } L (\text{trail } S) = \text{backtrack-lvl } S$ 
       $\implies \text{conflicting } S = C\text{-Clause } (D + \{\#L\# \})$ 
       $\implies \text{get-level } L (\text{trail } S) = \text{get-maximum-level } (D + \{\#L\# \}) (\text{trail } S)$ 

```

```

     $\Rightarrow$  get-maximum-level  $D$  (trail  $S$ )  $\equiv i$ 
     $\Rightarrow$  undefined-lit  $M1$   $L$ 
     $\Rightarrow T \sim \text{cons-trail } (\text{Propagated } L \ (D + \{\#L\# \}))$ 
      (reduce-trail-to  $M1$ 
        (add-learned-cls ( $D + \{\#L\# \}$ )
          (update-backtrack-lvl  $i$ 
            (update-conflicting  $C\text{-True } S$ ))))
     $\Rightarrow \text{cdcl}_W\text{-}M\text{-level-inv } S$ 
     $\Rightarrow P \ S \ T$ 
  shows  $P \ S \ T$ 
  using cdclW
proof (induct  $S \ T$  rule: cdclW-o-all-rules-induct)
  case (decide  $T$ )
  then show ?case by (elim decideE) (frule decideH; simp)
next
  case (backtrack  $S'$ )
  then show ?case
    using inv apply (induction rule: backtrack-induction-lev2)
    by (rule backtrackH)
    (fastforce simp del: state-simp simp add: state-eq-def dest!: HOL.meta-eq-to-obj-eq)+
next
  case (skip  $S'$ )
  then show ?case using skipH by auto
next
  case (resolve  $S'$ )
  then show ?case by (elim resolveE) (frule resolveH; simp)
qed

lemmas cdclW-o-induct-lev2 = cdclW-o-induct-lev[consumes 2, case-names decide skip resolve backtrack]

```

17.4.3 Compatibility with $op \sim$

```

lemma propagate-state-eq-compatible:
  assumes
    propagate  $S \ T$  and
     $S \sim S'$  and
     $T \sim T'$ 
  shows propagate  $S' \ T'$ 
  using assms apply (elim propagateE)
  apply (rule propagate-rule)
  by (auto simp: state-eq-def clauses-def simp del: state-simp)

```

```

lemma conflict-state-eq-compatible:
  assumes
    conflict  $S \ T$  and
     $S \sim S'$  and
     $T \sim T'$ 
  shows conflict  $S' \ T'$ 
  using assms apply (elim conflictE)
  apply (rule conflict-rule)
  by (auto simp: state-eq-def clauses-def simp del: state-simp)

```

```

lemma backtrack-state-eq-compatible:
  assumes
    backtrack  $S \ T$  and

```

$S \sim S'$ and
 $T \sim T'$ and
 $inv: cdcl_W\text{-}M\text{-level-inv } S$
shows *backtrack* $S' T'$
using *assms* **apply** (*induction rule: backtrack-induction-lev*)
using *inv* **apply** *simp*
apply (*rule backtrack-rule*)
apply *auto*[5]
by (*auto simp: state-eq-def clauses-def cdcl_W-M-level-inv-def simp del: state-simp*)

lemma *decide-state-eq-compatible:*

assumes
 $decide\ S\ T$ and
 $S \sim S'$ and
 $T \sim T'$
shows *decide* $S' T'$
using *assms* **apply** (*elim decideE*)
apply (*rule decide-rule*)
by (*auto simp: state-eq-def clauses-def simp del: state-simp*)

lemma *skip-state-eq-compatible:*

assumes
 $skip\ S\ T$ and
 $S \sim S'$ and
 $T \sim T'$
shows *skip* $S' T'$
using *assms* **apply** (*elim skipE*)
apply (*rule skip-rule*)
by (*auto simp: state-eq-def clauses-def HOL.eq-sym-conv[of - # - trail -]*
simp del: state-simp dest: arg-cong[of - # trail - trail - tl])

lemma *resolve-state-eq-compatible:*

assumes
 $resolve\ S\ T$ and
 $S \sim S'$ and
 $T \sim T'$
shows *resolve* $S' T'$
using *assms* **apply** (*elim resolveE*)
apply (*rule resolve-rule*)
by (*auto simp: state-eq-def clauses-def HOL.eq-sym-conv[of - # - trail -]*
simp del: state-simp dest: arg-cong[of - # trail - trail - tl])

lemma *forget-state-eq-compatible:*

assumes
 $forget\ S\ T$ and
 $S \sim S'$ and
 $T \sim T'$
shows *forget* $S' T'$
using *assms* **apply** (*elim forgetE*)
apply (*rule forget-rule*)
by (*auto simp: state-eq-def clauses-def HOL.eq-sym-conv[of {#-#} + - -]*
simp del: state-simp dest: arg-cong[of - # trail - trail - tl])

lemma *cdcl_W-state-eq-compatible:*

assumes

$cdcl_W S T$ and $\neg restart S T$ and
 $S \sim S'$ and
 $T \sim T'$ and
 $inv: cdcl_W\text{-}M\text{-level-inv } S$
shows $cdcl_W S' T'$
using *assms* **by** (*meson* *assms* *backtrack-state-eq-compatible* *bj* $cdcl_W.simps$ $cdcl_W\text{-}bj.simps$
 $cdcl_W\text{-}o\text{-rule-cases}$ $cdcl_W\text{-}rf.cases$ $cdcl_W\text{-}rf.restart$ *conflict-state-eq-compatible* *decide*
decide-state-eq-compatible *forget* *forget-state-eq-compatible*
propagate-state-eq-compatible *resolve-state-eq-compatible*
skip-state-eq-compatible)

17.4.4 Conservation of some Properties

lemma *level-of-marked-ge-1*:

assumes
 $cdcl_W S S'$ and
 $inv: cdcl_W\text{-}M\text{-level-inv } S$ and
 $\forall L l. \text{Marked } L l \in \text{set } (trail S) \longrightarrow l > 0$
shows $\forall L l. \text{Marked } L l \in \text{set } (trail S') \longrightarrow l > 0$
using *assms* **apply** (*induct* *rule*: $cdcl_W\text{-}all\text{-induct-lev2}$)
by (*auto* *dest*: *union-in-get-all-marked-decomposition-is-subset* *simp*: $cdcl_W\text{-}M\text{-level-inv-decomp}$)

lemma *cdcl_W-o-no-more-init-clss*:

assumes
 $cdcl_W\text{-}o S S'$ and
 $inv: cdcl_W\text{-}M\text{-level-inv } S$
shows $init\text{-}clss S = init\text{-}clss S'$
using *assms* **by** (*induct* *rule*: $cdcl_W\text{-}o\text{-induct-lev2}$) (*auto* *simp*: $cdcl_W\text{-}M\text{-level-inv-decomp}$)

lemma *trancpl-cdcl_W-o-no-more-init-clss*:

assumes
 $cdcl_W\text{-}o^{++} S S'$ and
 $inv: cdcl_W\text{-}M\text{-level-inv } S$
shows $init\text{-}clss S = init\text{-}clss S'$
using *assms* **apply** (*induct* *rule*: *trancpl.induct*)
by (*auto* *dest*: $cdcl_W\text{-}o\text{-no-more-init-clss}$
dest!: $trancpl\text{-}cdcl_W\text{-}consistent\text{-}inv$ *dest*: $trancpl\text{-}mono\text{-}explicit[of\ cdcl_W\text{-}o - - cdcl_W]$
simp: *other*)

lemma *rtrancpl-cdcl_W-o-no-more-init-clss*:

assumes
 $cdcl_W\text{-}o^{**} S S'$ and
 $inv: cdcl_W\text{-}M\text{-level-inv } S$
shows $init\text{-}clss S = init\text{-}clss S'$
using *assms* **unfolding** *rtrancpl-unfold* **by** (*auto* *intro*: $trancpl\text{-}cdcl_W\text{-}o\text{-no-more-init-clss}$)

lemma *cdcl_W-init-clss*:

$cdcl_W S T \Longrightarrow cdcl_W\text{-}M\text{-level-inv } S \Longrightarrow init\text{-}clss S = init\text{-}clss T$
by (*induct* *rule*: $cdcl_W\text{-}all\text{-induct-lev2}$) (*auto* *simp*: $cdcl_W\text{-}M\text{-level-inv-def}$)

lemma *rtrancpl-cdcl_W-init-clss*:

$cdcl_W^{**} S T \Longrightarrow cdcl_W\text{-}M\text{-level-inv } S \Longrightarrow init\text{-}clss S = init\text{-}clss T$
by (*induct* *rule*: *rtrancpl-induct*) (*auto* *dest*: $cdcl_W\text{-}init\text{-}clss$ *rtrancpl-cdcl_W-consistent-inv*)

lemma *trancpl-cdcl_W-init-clss*:

$cdcl_W^{++} S T \Longrightarrow cdcl_W\text{-}M\text{-level-inv } S \Longrightarrow init\text{-}clss S = init\text{-}clss T$

using *rtrancp-cdcl_W-init-clss*[of *S T*] **unfolding** *rtrancp-unfold* **by** *auto*

17.4.5 Learned Clause

This invariant shows that:

- the learned clauses are entailed by the initial set of clauses.
- the conflicting clause is entailed by the initial set of clauses.
- the marks are entailed by the clauses. A more precise version would be to show that either these marked are learned or are in the set of clauses

definition *cdcl_W-learned-clause* (*S*:: *'st*) \longleftrightarrow
(init-clss S \models_{psm} learned-clss S
 $\wedge (\forall T. \text{conflicting } S = C\text{-Clause } T \longrightarrow \text{init-clss } S \models_{pm} T)$
 $\wedge \text{set } (\text{get-all-mark-of-propagated } (\text{trail } S)) \subseteq \text{set-mset } (\text{clauses } S))$

lemma *cdcl_W-learned-clause-S0-cdcl_W[simp]*:
cdcl_W-learned-clause (*init-state N*)
unfolding *cdcl_W-learned-clause-def* **by** *auto*

lemma *cdcl_W-learned-clss*:

assumes

cdcl_W S S' **and**

learned: cdcl_W-learned-clause S **and**

lev-inv: cdcl_W-M-level-inv S

shows *cdcl_W-learned-clause S'*

using *assms(1) lev-inv learned*

proof (*induct rule: cdcl_W-all-induct-lev2*)

case (*backtrack K i M1 M2 L D T*) **note** *decomp = this(1)* **and** *confl = this(3)* **and** *undef = this(6)*
and *T = this(7)*

show *?case*

using *decomp confl learned undef T lev-inv* **unfolding** *cdcl_W-learned-clause-def*

by (*auto dest!: get-all-marked-decomposition-exists-prepend*

simp: clauses-def cdcl_W-M-level-inv-decomp dest: true-clss-clss-left-right)

next

case (*resolve L C M D*) **note** *trail = this(1)* **and** *confl = this(2)* **and** *lvl = this(3)* **and**
T = this(4)

moreover

have *init-clss S \models_{psm} learned-clss S*

using *learned trail* **unfolding** *cdcl_W-learned-clause-def clauses-def* **by** *auto*

then have *init-clss S \models_{pm} C + {#L#}*

using *trail learned* **unfolding** *cdcl_W-learned-clause-def clauses-def*

by (*auto dest: true-clss-clss-in-imp-true-clss-clss*)

ultimately show *?case*

using *learned*

by (*auto dest: mk-disjoint-insert true-clss-clss-left-right*

simp add: cdcl_W-learned-clause-def clauses-def

intro: true-clss-clss-union-mset-true-clss-clss-or-not-true-clss-clss-or)

next

case (*restart T*)

then show *?case*

using *learned-clss-restart-state*[of *T*]

```

  by (auto dest!: get-all-marked-decomposition-exists-prepend
    simp: clauses-def state-eq-def cdclW-learned-clause-def
    simp del: state-simp
    dest: true-clss-clssm-subsetE)
next
case propagate
then show ?case using learned by (auto simp: cdclW-learned-clause-def clauses-def)
next
case conflict
then show ?case using learned
  by (auto simp: cdclW-learned-clause-def clauses-def true-clss-clss-in-imp-true-clss-clss)
next
case forget
then show ?case
  using learned by (auto simp: cdclW-learned-clause-def clauses-def split: split-if-asm)
qed (auto simp: cdclW-learned-clause-def clauses-def)

lemma rtranclp-cdclW-learned-clss:
  assumes
    cdclW** S S' and
    cdclW-M-level-inv S
    cdclW-learned-clause S
  shows cdclW-learned-clause S'
  using assms by induction (auto dest: cdclW-learned-clss intro: rtranclp-cdclW-consistent-inv)

```

17.4.6 No alien atom in the state

This invariant means that all the literals are in the set of clauses.

definition *no-strange-atm* $S' \longleftrightarrow$ (
 $(\forall T. \text{conflicting } S' = C\text{-Clause } T \longrightarrow \text{atms-of } T \subseteq \text{atms-of-msu } (\text{init-clss } S'))$
 $\wedge (\forall L \text{ mark. Propagated } L \text{ mark} \in \text{set } (\text{trail } S') \longrightarrow \text{atms-of } (\text{mark}) \subseteq \text{atms-of-msu } (\text{init-clss } S'))$
 $\wedge \text{atms-of-msu } (\text{learned-clss } S') \subseteq \text{atms-of-msu } (\text{init-clss } S')$
 $\wedge \text{atm-of } ' (\text{lits-of } (\text{trail } S')) \subseteq \text{atms-of-msu } (\text{init-clss } S')$)

lemma *no-strange-atm-decomp*:
 assumes *no-strange-atm* S
 shows *conflicting* S = C-Clause T $\implies \text{atms-of } T \subseteq \text{atms-of-msu } (\text{init-clss } S)$
 and $(\forall L \text{ mark. Propagated } L \text{ mark} \in \text{set } (\text{trail } S) \longrightarrow \text{atms-of } (\text{mark}) \subseteq \text{atms-of-msu } (\text{init-clss } S))$
 and $\text{atms-of-msu } (\text{learned-clss } S) \subseteq \text{atms-of-msu } (\text{init-clss } S)$
 and $\text{atm-of } ' (\text{lits-of } (\text{trail } S)) \subseteq \text{atms-of-msu } (\text{init-clss } S)$
 using assms unfolding *no-strange-atm-def* by blast+

lemma *no-strange-atm-S0* [simp]: *no-strange-atm* (init-state N)
 unfolding *no-strange-atm-def* by auto

lemma *cdcl_W-no-strange-atm-explicit*:
 assumes
 cdcl_W S S' and
 lev: cdcl_W-M-level-inv S and
 conf: $\forall T. \text{conflicting } S = C\text{-Clause } T \longrightarrow \text{atms-of } T \subseteq \text{atms-of-msu } (\text{init-clss } S)$ and
 marked: $\forall L \text{ mark. Propagated } L \text{ mark} \in \text{set } (\text{trail } S) \longrightarrow \text{atms-of } \text{mark} \subseteq \text{atms-of-msu } (\text{init-clss } S)$ and
 learned: $\text{atms-of-msu } (\text{learned-clss } S) \subseteq \text{atms-of-msu } (\text{init-clss } S)$ and

$trail: atm-of \text{ ' } (lits-of (trail S)) \subseteq atms-of-msu (init-clss S)$
shows $(\forall T. \text{ conflicting } S' = C\text{-Clause } T \longrightarrow atms-of T \subseteq atms-of-msu (init-clss S')) \wedge$
 $(\forall L \text{ mark. Propagated } L \text{ mark} \in set (trail S'))$
 $\longrightarrow atms-of (\text{ mark}) \subseteq atms-of-msu (init-clss S')) \wedge$
 $atms-of-msu (learned-clss S') \subseteq atms-of-msu (init-clss S') \wedge$
 $atm-of \text{ ' } (lits-of (trail S')) \subseteq atms-of-msu (init-clss S') \text{ (is } ?C S' \wedge ?M S' \wedge ?U S' \wedge ?V S')$
using $assms(1,2)$
proof (*induct rule: cdcl_W-all-induct-lev2*)
case (*propagate C L T*) **note** $C-L = this(1)$ **and** $undef = this(3)$ **and** $confl = this(4)$ **and** $T = this(5)$
have $?C (cons-trail (Propagated L (C + \{\#L\# \})) S)$ **using** $confl undef$ **by** *auto*
moreover
have $atms-of (C + \{\#L\# \}) \subseteq atms-of-msu (init-clss S)$
by (*metis (no-types) atms-of-atms-of-ms-mono atms-of-ms-union clauses-def mem-set-mset-iff*
 $C-L \text{ learned set-mset-union sup.orderE}$)
then have $?M (cons-trail (Propagated L (C + \{\#L\# \})) S)$ **using** $undef$
by (*simp add: marked*)
moreover have $?U (cons-trail (Propagated L (C + \{\#L\# \})) S)$
using $learned undef$ **by** *auto*
moreover have $?V (cons-trail (Propagated L (C + \{\#L\# \})) S)$
using $C-L \text{ learned trail undef unfolding clauses-def}$
by (*auto simp: in-plus-implies-atm-of-on-atms-of-ms*)
ultimately show $?case$ **using** T **by** *auto*
next
case (*decide L*)
then show $?case$ **using** $learned marked confl trail unfolding clauses-def$ **by** *auto*
next
case (*skip L C M D*)
then show $?case$ **using** $learned marked confl trail$ **by** *auto*
next
case (*conflict D T*) **note** $T = this(4)$
have $D: atm-of \text{ ' } set-mset D \subseteq \bigcup (atms-of \text{ ' } (set-mset (clauses S)))$
using $\langle D \in \# clauses S \rangle$ **by** (*auto simp add: atms-of-def atms-of-ms-def*)
moreover {
fix $xa :: 'v \text{ literal}$
assume $a1: atm-of \text{ ' } set-mset D \subseteq (\bigcup x \in set-mset (init-clss S). atms-of x)$
 $\cup (\bigcup x \in set-mset (learned-clss S). atms-of x)$
assume $a2: (\bigcup x \in set-mset (learned-clss S). atms-of x) \subseteq (\bigcup x \in set-mset (init-clss S). atms-of x)$
assume $xa \in \# D$
then have $atm-of xa \in UNION (set-mset (init-clss S)) atms-of$
using $a2 a1$ **by** (*metis (no-types) Un-iff atm-of-lit-in-atms-of atms-of-def subset-Un-eq*)
then have $\exists m \in set-mset (init-clss S). atm-of xa \in atms-of m$
by *blast*
} **note** $H = this$
ultimately show $?case$ **using** $conflict.prems T$ $learned marked confl trail$
unfolding $atms-of-def atms-of-ms-def clauses-def$
by (*auto simp add: H*)
next
case (*restart T*)
then show $?case$ **using** $learned marked confl trail$ **by** *auto*
next
case (*forget C T*) **note** $C = this(3)$ **and** $C-le = this(4)$ **and** $confl = this(5)$ **and**
 $T = this(6)$
have $H: \bigwedge L \text{ mark. Propagated } L \text{ mark} \in set (trail S) \implies atms-of mark \subseteq atms-of-msu (init-clss S)$
using $marked$ **by** *simp*
show $?case$ **unfolding** $clauses-def$ **apply** *standard*

```

    using conf T trail C unfolding clauses-def apply (auto dest!: H)[]
    apply standard
    using T trail C apply (auto dest!: H)[]
    apply standard
    using T learned C C-le atms-of-ms-remove-subset[of set-mset (learned-clss S)] apply (auto)[]
    using T trail C apply (auto simp: clauses-def lits-of-def)[]
done
next
case (backtrack K i M1 M2 L D T) note decomp = this(1) and confl = this(3) and undef = this(6)
  and T = this(7)
have ?C T
  using conf T decomp undef lev by (auto simp: cdclW-M-level-inv-decomp)
moreover have set M1 ⊆ set (trail S)
  using backtrack.hyps(1) by auto
then have M: ?M T
  using marked conf undef confl T decomp lev
  by (auto simp: image-subset-iff clauses-def cdclW-M-level-inv-decomp)
moreover have ?U T
  using learned decomp conf confl T undef lev unfolding clauses-def
  by (auto simp: cdclW-M-level-inv-decomp)
moreover have ?V T
  using M conf confl trail T undef decomp lev by (force simp: cdclW-M-level-inv-decomp)
ultimately show ?case by blast
next
case (resolve L C M D T) note trail-S = this(1) and confl = this(2) and T = this(4)
let ?T = update-conflicting (C-Clause (remdups-mset (D + C))) (tl-trail S)
have ?C ?T
  using confl trail-S conf marked by simp
moreover have ?M ?T
  using confl trail-S conf marked by auto
moreover have ?U ?T
  using trail learned by auto
moreover have ?V ?T
  using confl trail-S trail by auto
ultimately show ?case using T by auto
qed

```

lemma *cdcl_W-no-strange-atm-inv*:

assumes *cdcl_W S S' and no-strange-atm S and cdcl_W-M-level-inv S*

shows *no-strange-atm S'*

using *cdcl_W-no-strange-atm-explicit[OF assms(1)] assms(2,3) unfolding no-strange-atm-def by fast*

lemma *rtranclp-cdcl_W-no-strange-atm-inv*:

assumes *cdcl_W** S S' and no-strange-atm S and cdcl_W-M-level-inv S*

shows *no-strange-atm S'*

using *assms by induction (auto intro: cdcl_W-no-strange-atm-inv rtranclp-cdcl_W-consistent-inv)*

17.4.7 No duplicates all around

This invariant shows that there is no duplicate (no literal appearing twice in the formula). The last part could be proven using the previous invariant moreover.

definition *distinct-cdcl_W-state* (*S::'st*)

$\longleftrightarrow ((\forall T. \text{conflicting } S = \text{C-Clause } T \longrightarrow \text{distinct-mset } T)$

$\wedge \text{distinct-mset-mset (learned-clss } S)$

$\wedge \text{distinct-mset-mset (init-clss } S)$

$\wedge (\forall L \text{ mark. } (\text{Propagated } L \text{ mark} \in \text{set } (\text{trail } S) \longrightarrow \text{distinct-mset } (\text{mark}))))$

lemma *distinct-cdcl_W-state-decomp*:

assumes *distinct-cdcl_W-state* (*S::'st*)

shows $\forall T. \text{conflicting } S = C\text{-Clause } T \longrightarrow \text{distinct-mset } T$

and *distinct-mset-mset* (*learned-clss* *S*)

and *distinct-mset-mset* (*init-clss* *S*)

and $\forall L \text{ mark. } (\text{Propagated } L \text{ mark} \in \text{set } (\text{trail } S) \longrightarrow \text{distinct-mset } (\text{mark}))$

using *assms* **unfolding** *distinct-cdcl_W-state-def* **by** *blast+*

lemma *distinct-cdcl_W-state-decomp-2*:

assumes *distinct-cdcl_W-state* (*S::'st*)

shows *conflicting* *S* \implies *C-Clause* *T* \implies *distinct-mset* *T*

using *assms* **unfolding** *distinct-cdcl_W-state-def* **by** *auto*

lemma *distinct-cdcl_W-state-S0-cdcl_W[simp]*:

distinct-mset-mset *N* \implies *distinct-cdcl_W-state* (*init-state* *N*)

unfolding *distinct-cdcl_W-state-def* **by** *auto*

lemma *distinct-cdcl_W-state-inv*:

assumes

cdcl_W *S* *S'* **and**

cdcl_W-M-level-inv *S* **and**

distinct-cdcl_W-state *S*

shows *distinct-cdcl_W-state* *S'*

using *assms*

proof (*induct* *rule*: *cdcl_W-all-induct-lev2*)

case (*backtrack* *K* *i* *M1* *M2* *L* *D*)

then show *?case*

unfolding *distinct-cdcl_W-state-def*

by (*fastforce* *dest*: *get-all-marked-decomposition-incl simp: cdcl_W-M-level-inv-decomp*)

next

case *restart*

then show *?case* **unfolding** *distinct-cdcl_W-state-def* *distinct-mset-set-def* *clauses-def*

using *learned-clss-restart-state[of S]* **by** *auto*

next

case *resolve*

then show *?case*

by (*auto simp add: distinct-cdcl_W-state-def* *distinct-mset-set-def* *clauses-def*

distinct-mset-single-add

intro!: *distinct-mset-union-mset*)

qed (*auto simp add: distinct-cdcl_W-state-def* *distinct-mset-set-def* *clauses-def*)

lemma *rtanclp-distinct-cdcl_W-state-inv*:

assumes

*cdcl_W*** *S* *S'* **and**

cdcl_W-M-level-inv *S* **and**

distinct-cdcl_W-state *S*

shows *distinct-cdcl_W-state* *S'*

using *assms* **apply** (*induct* *rule*: *rtanclp-induct*)

using *distinct-cdcl_W-state-inv* *rtanclp-cdcl_W-consistent-inv* **by** *blast+*

17.4.8 Conflicts and co

This invariant shows that each mark contains a contradiction only related to the previously defined variable.

abbreviation *every-mark-is-a-conflict* :: 'st \Rightarrow bool **where**

every-mark-is-a-conflict $S \equiv$

$\forall L \text{ mark } a \text{ b. } a @ \text{Propagated } L \text{ mark } \# b = (\text{trail } S)$
 $\longrightarrow (b \models_{as} CNot (\text{mark} - \{\#L\}) \wedge L \in \# \text{ mark})$

definition *cdcl_W-conflicting* $S \equiv$

$(\forall T. \text{conflicting } S = C\text{-Clause } T \longrightarrow \text{trail } S \models_{as} CNot T)$
 $\wedge \text{every-mark-is-a-conflict } S$

lemma *backtrack-atms-of-D-in-M1*:

fixes $M1 :: ('v, nat, 'v \text{ clause}) \text{ marked-lits}$

assumes

inv: *cdcl_W-M-level-inv* S **and**

undef: *undefined-lit* $M1 \ L$ **and**

i: *get-maximum-level* $D (\text{trail } S) = i$ **and**

decomp: $(\text{Marked } K (\text{Suc } i) \# M1, M2)$

$\in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$ **and**

S-lvl: *backtrack-lvl* $S = \text{get-maximum-level } (D + \{\#L\}) (\text{trail } S)$ **and**

S-conf: *conflicting* $S = C\text{-Clause } (D + \{\#L\})$ **and**

undef: *undefined-lit* $M1 \ L$ **and**

T: $T \sim (\text{cons-trail } (\text{Propagated } L (D + \{\#L\})))$

$(\text{reduce-trail-to } M1$

$(\text{add-learned-cls } (D + \{\#L\})$

$(\text{update-backtrack-lvl } i$

$(\text{update-conflicting } C\text{-True } S))))$ **and**

confl: $\forall T. \text{conflicting } S = C\text{-Clause } T \longrightarrow \text{trail } S \models_{as} CNot T$

shows *atms-of* $D \subseteq \text{atm-of ' lits-of } (tl (\text{trail } T))$

proof (rule *ccontr*)

let $?k = \text{get-maximum-level } (D + \{\#L\}) (\text{trail } S)$

have $\text{trail } S \models_{as} CNot D$ **using** *confl* *S-conf* **by** *auto*

then have *vars-of-D*: *atms-of* $D \subseteq \text{atm-of ' lits-of } (\text{trail } S)$ **unfolding** *atms-of-def*

by (*meson image-subsetI mem-set-mset-iff true-annots-CNot-all-atms-defined*)

obtain $M0$ **where** $M: \text{trail } S = M0 @ M2 @ \text{Marked } K (\text{Suc } i) \# M1$

using *decomp* **by** *auto*

have *max*: *get-maximum-level* $(D + \{\#L\}) (\text{trail } S)$

$= \text{length } (\text{get-all-levels-of-marked } (M0 @ M2 @ \text{Marked } K (\text{Suc } i) \# M1))$

using *inv* **unfolding** *cdcl_W-M-level-inv-def* *S-lvl* M **by** *simp*

assume $a: \neg ?thesis$

then obtain L' **where**

$L': L' \in \text{atms-of } D$ **and**

$L'\text{-notin-}M1: L' \notin \text{atm-of ' lits-of } M1$

using $T \text{ undef decomp inv}$ **by** (*auto simp: cdcl_W-M-level-inv-decomp*)

then have $L'\text{-in}$: $L' \in \text{atm-of ' lits-of } (M0 @ M2 @ \text{Marked } K (i + 1) \# [])$

using *vars-of-D* **unfolding** M **by** *force*

then obtain L'' **where**

$L'' \in \# D$ **and**

$L'': L' = \text{atm-of } L''$

using $L' L'\text{-notin-}M1$ **unfolding** *atms-of-def* **by** *auto*

have *get-level* $L'' (\text{trail } S) = \text{get-rev-level } L'' (\text{Suc } i) (\text{Marked } K (\text{Suc } i) \# \text{rev } M2 @ \text{rev } M0)$

```

    using L'-notin-M1 L'' M by (auto simp del: get-rev-level.simps)
  have get-all-levels-of-marked (trail S) = rev [1.. $1+k$ ]
    using inv S-lvl unfolding cdclW-M-level-inv-def by auto
  then have get-all-levels-of-marked (M0 @ M2)
    = rev [Suc (Suc i).. $\text{Suc } (\text{get-maximum-level } (D + \{\#L\# \}) (\text{trail } S))$ ]
    unfolding M by (auto simp: rev-swap[symmetric] dest!: append-cons-eq-upt-length-i-end)

  then have M: get-all-levels-of-marked M0 @ get-all-levels-of-marked M2
    = rev [Suc (Suc i).. $\text{Suc } (\text{length } (\text{get-all-levels-of-marked } (M0 @ M2 @ \text{Marked } K (\text{Suc } i) \# M1)))$ ]
    unfolding max unfolding M by simp

  have get-rev-level L'' (Suc i) (Marked K (Suc i) # rev (M0 @ M2))
     $\geq \text{Min } (\text{set } ((\text{Suc } i) \# \text{get-all-levels-of-marked } (\text{Marked } K (\text{Suc } i) \# \text{rev } (M0 @ M2))))$ 
    using get-rev-level-ge-min-get-all-levels-of-marked[of L''
      rev (M0 @ M2 @ [Marked K (Suc i)]) Suc i] L'-in
    unfolding L'' by (fastforce simp add: lits-of-def)
  also have Min (set ((Suc i) # get-all-levels-of-marked (Marked K (Suc i) # rev (M0 @ M2))))
    = Min (set ((Suc i) # get-all-levels-of-marked (rev (M0 @ M2)))) by auto
  also have ... = Min (set ((Suc i) # get-all-levels-of-marked M0 @ get-all-levels-of-marked M2))
    by (simp add: Un-commute)
  also have ... = Min (set ((Suc i) # [Suc (Suc i).. $2 + \text{length } (\text{get-all-levels-of-marked } M0)$ 
    +  $(\text{length } (\text{get-all-levels-of-marked } M2) + \text{length } (\text{get-all-levels-of-marked } M1))$ ]))
    unfolding M by (auto simp add: Un-commute)
  also have ... = Suc i by (auto intro: Min-eqI)
  finally have get-rev-level L'' (Suc i) (Marked K (Suc i) # rev (M0 @ M2))  $\geq \text{Suc } i$  .
  then have get-level L'' (trail S)  $\geq i + 1$ 
    using  $\langle \text{get-level } L'' (\text{trail } S) = \text{get-rev-level } L'' (\text{Suc } i) (\text{Marked } K (\text{Suc } i) \# \text{rev } M2 @ \text{rev } M0) \rangle$ 
    by simp
  then have get-maximum-level D (trail S)  $\geq i + 1$ 
    using get-maximum-level-ge-get-level[OF  $\langle L'' \in \# D \rangle$ , of trail S] by auto
  then show False using i by auto
qed

```

lemma distinct-atms-of-incl-not-in-other:

```

  assumes a1: no-dup (M @ M')
  and a2: atms-of D  $\subseteq \text{atm-of ' lits-of } M'$ 
  shows  $\forall x \in \text{atms-of } D. x \notin \text{atm-of ' lits-of } M$ 
proof -
  { fix aa :: 'a
    have ff1:  $\bigwedge l \text{ ms. undefined-lit } ms \ l \vee \text{atm-of } l$ 
       $\in \text{set } (\text{map } (\lambda m. \text{atm-of } (\text{lit-of } (m::('a, 'b, 'c) \text{ marked-lit}))) \text{ ms})$ 
      by (simp add: defined-lit-map)
    have ff2:  $\bigwedge a. a \notin \text{atms-of } D \vee a \in \text{atm-of ' lits-of } M'$ 
      using a2 by (meson subsetCE)
    have ff3:  $\bigwedge a. a \notin \text{set } (\text{map } (\lambda m. \text{atm-of } (\text{lit-of } m)) M') \vee a \notin \text{set } (\text{map } (\lambda m. \text{atm-of } (\text{lit-of } m)) M)$ 
      using a1 by (metis (lifting) IntI distinct-append empty-iff map-append)
    have  $\forall L \text{ a f. } \exists l. ((a::'a) \notin f \text{ ' } L \vee (l::'a \text{ literal}) \in L) \wedge (a \notin f \text{ ' } L \vee f \ l = a)$ 
      by blast
    then have aa  $\notin \text{atms-of } D \vee aa \notin \text{atm-of ' lits-of } M$ 
      using ff3 ff2 ff1 by (metis (no-types) Marked-Propagated-in-iff-in-lits-of) }
  then show ?thesis
    by blast
qed

```

```

lemma cdclW-propagate-is-conclusion:
  assumes
    cdclW S S' and
    inv: cdclW-M-level-inv S and
    decomp: all-decomposition-implies-m (init-clss S) (get-all-marked-decomposition (trail S)) and
    learned: cdclW-learned-clause S and
    conft:  $\forall T. \text{conflicting } S = C\text{-Clause } T \longrightarrow \text{trail } S \models_{as} CNot\ T$  and
    alien: no-strange-atm S
  shows all-decomposition-implies-m (init-clss S') (get-all-marked-decomposition (trail S'))
  using assms(1,2)
proof (induct rule: cdclW-all-induct-lev2)
  case restart
  then show ?case by auto
next
  case forget
  then show ?case using decomp by auto
next
  case conflict
  then show ?case using decomp by auto
next
  case (resolve L C M D) note tr = this(1) and T = this(4)
  let ?decomp = get-all-marked-decomposition M
  have M: set ?decomp = insert (hd ?decomp) (set (tl ?decomp))
    by (cases ?decomp) auto
  show ?case
    using decomp tr T unfolding all-decomposition-implies-def
    by (cases hd (get-all-marked-decomposition M))
      (auto simp: M)
next
  case (skip L C' M D) note tr = this(1) and T = this(5)
  have M: set (get-all-marked-decomposition M)
    = insert (hd (get-all-marked-decomposition M)) (set (tl (get-all-marked-decomposition M)))
    by (cases get-all-marked-decomposition M) auto
  show ?case
    using decomp tr T unfolding all-decomposition-implies-def
    by (cases hd (get-all-marked-decomposition M))
      (auto simp add: M)
next
  case decide note S = this(1) and undef = this(2) and T = this(4)
  show ?case using decomp T undef unfolding S all-decomposition-implies-def by auto
next
  case (propagate C L T) note propa = this(2) and undef = this(3) and T = this(5)
  obtain a y where ay: hd (get-all-marked-decomposition (trail S)) = (a, y)
    by (cases hd (get-all-marked-decomposition (trail S)))
  then have M: trail S = y @ a using get-all-marked-decomposition-decomp by blast
  have M': set (get-all-marked-decomposition (trail S))
    = insert (a, y) (set (tl (get-all-marked-decomposition (trail S))))
    using ay by (cases get-all-marked-decomposition (trail S)) auto
  have ( $\lambda a. \{\#lit\text{-of } a\# \}$ ) ‘ set a  $\cup$  set-mset (init-clss S)  $\models_{ps}$  ( $\lambda a. \{\#lit\text{-of } a\# \}$ ) ‘ set y
    using decomp ay unfolding all-decomposition-implies-def
    by (cases get-all-marked-decomposition (trail S)) fastforce+
  then have a-Un-N-M: ( $\lambda a. \{\#lit\text{-of } a\# \}$ ) ‘ set a  $\cup$  set-mset (init-clss S)
     $\models_{ps}$  ( $\lambda a. \{\#lit\text{-of } a\# \}$ ) ‘ set (trail S)
    unfolding M by (auto simp add: all-in-true-clss-clss image-Un)

```

```

have (λa. {#lit-of a#}) ‘ set a ∪ set-mset (init-clss S) ⊨p {#L#} (is ?I ⊨p -)
proof (rule true-clss-clss-plus-CNot)
  show ?I ⊨p C + {#L#}
  using propa propagate.premis learned confl unfolding M
  by (metis Un-iff cdclW-learned-clause-def clauses-def mem-set-mset-iff propagate.hyps(1)
      set-mset-union true-clss-clss-in-imp-true-clss-clss true-clss-clss-mono-l2
      union-trus-clss-clss)
next
have (λm. {#lit-of m#}) ‘ set (trail S) ⊨ps CNot C
  using (⟨trail S⟩ ⊨as CNot C) true-annots-true-clss-clss by blast
then show ?I ⊨ps CNot C
  using a-Un-N-M true-clss-clss-left-right true-clss-clss-union-l-r by blast
qed
moreover have ∧aa b.
  ∀ (Ls, seen) ∈ set (get-all-marked-decomposition (y @ a)).
  (λa. {#lit-of a#}) ‘ set Ls ∪ set-mset (init-clss S) ⊨ps (λa. {#lit-of a#}) ‘ set seen
  ⇒ (aa, b) ∈ set (tl (get-all-marked-decomposition (y @ a)))
  ⇒ (λa. {#lit-of a#}) ‘ set aa ∪ set-mset (init-clss S) ⊨ps (λa. {#lit-of a#}) ‘ set b
  by (metis (no-types, lifting) case-prod-conv get-all-marked-decomposition-never-empty-sym
      list.collapse list.set-intros(2))

ultimately show ?case
  using decomp T undef unfolding ay all-decomposition-implies-def
  using M (λa. {#lit-of a#}) ‘ set a ∪ set-mset (init-clss S) ⊨ps (λa. {#lit-of a#}) ‘ set y
  ay by auto
next
case (backtrack K i M1 M2 L D T) note decomp' = this(1) and lev-L = this(2) and conf = this(3)
and
  undef = this(6) and T = this(7)
have ∀ l ∈ set M2. ¬is-marked l
  using get-all-marked-decomposition-snd-not-marked backtrack.hyps(1) by blast
obtain M0 where M: trail S = M0 @ M2 @ Marked K (i + 1) # M1
  using decomp' by auto
show ?case unfolding all-decomposition-implies-def
proof
  fix x
  assume x ∈ set (get-all-marked-decomposition (trail T))
  then have x: x ∈ set (get-all-marked-decomposition (Propagated L ((D + {#L#})) # M1))
    using T decomp' undef inv by (simp add: cdclW-M-level-inv-decomp)
  let ?m = get-all-marked-decomposition (Propagated L ((D + {#L#})) # M1)
  let ?hd = hd ?m
  let ?tl = tl ?m
  have x = ?hd ∨ x ∈ set ?tl
    using x by (case-tac ?m) auto
  moreover {
    assume x ∈ set ?tl
    then have x ∈ set (get-all-marked-decomposition (trail S))
      using tl-get-all-marked-decomposition-skip-some[of x] by (simp add: list.set-sel(2) M)
    then have case x of (Ls, seen) ⇒ (λa. {#lit-of a#}) ‘ set Ls
      ∪ set-mset (init-clss (T))
      ⊨ps (λa. {#lit-of a#}) ‘ set seen
    using decomp learned decomp confl alien inv T undef M
    unfolding all-decomposition-implies-def cdclW-M-level-inv-def
    by auto
  }

```

```

moreover {
  assume  $x = ?hd$ 
  obtain  $M1' M1''$  where  $M1: hd (get-all-marked-decomposition M1) = (M1', M1'')$ 
    by (cases  $hd (get-all-marked-decomposition M1)$ )
  then have  $x': x = (M1', Propagated L (D + \{\#L\})) \# M1''$ 
    using  $\langle x = ?hd \rangle$  by auto
  have  $(M1', M1'') \in set (get-all-marked-decomposition (trail S))$ 
    using  $M1[symmetric]$  hd-get-all-marked-decomposition-skip-some[OF  $M1[symmetric]$ ,
      of  $M0 @ M2 - i + 1$ ] unfolding  $M$  by fastforce
  then have  $1: (\lambda a. \{\#lit-of a\# \}) ' set M1' \cup set-mset (init-clss S)$ 
     $\models_{ps} (\lambda a. \{\#lit-of a\# \}) ' set M1''$ 
    using decomp unfolding all-decomposition-implies-def by auto
moreover
  have  $trail S \models_{as} CNot D$  using conf confl by auto
  then have  $vars-of-D: atms-of D \subseteq atm-of ' lits-of (trail S)$ 
    unfolding atms-of-def
    by (meson image-subsetI mem-set-mset-iff true-annots-CNot-all-atms-defined)
  have  $vars-of-D: atms-of D \subseteq atm-of ' lits-of M1$ 
    using backtrack-atms-of-D-in-M1[of  $S M1 L D i K M2 T$ ] backtrack inv conf confl
    by (auto simp: cdclW-M-level-inv-decomp)
  have no-dup ( $trail S$ ) using inv by (auto simp: cdclW-M-level-inv-decomp)
  then have vars-in-M1:
     $\forall x \in atms-of D. x \notin atm-of ' lits-of (M0 @ M2 @ Marked K (i + 1) \# \square)$ 
    using vars-of-D distinct-atms-of-incl-not-in-other[of  $M0 @ M2 @ Marked K (i + 1) \# \square$ 
       $M1$ ]
    unfolding  $M$  by auto
  have  $M1 \models_{as} CNot D$ 
    using vars-in-M1 true-annots-remove-if-notin-vars[of  $M0 @ M2 @ Marked K (i + 1) \# \square$ 
       $M1 CNot D$ ]  $\langle trail S \models_{as} CNot D \rangle$  unfolding M lits-of-def by simp
  have  $M1 = M1'' @ M1'$  by (simp add: M1 get-all-marked-decomposition-decomp)
  have  $TT: (\lambda a. \{\#lit-of a\# \}) ' set M1' \cup set-mset (init-clss S) \models_{ps} CNot D$ 
    using true-annots-true-clss-cl[OF  $\langle M1 \models_{as} CNot D \rangle$ ] true-clss-clss-left-right[OF  $1,$ 
      of  $CNot D$ ] unfolding  $\langle M1 = M1'' @ M1' \rangle$  by (auto simp add: inf-sup-aci(5,7))
  have  $init-clss S \models_{pm} D + \{\#L\# \}$ 
    using conf learned cdclW-learned-clause-def confl by blast
  then have  $T': (\lambda a. \{\#lit-of a\# \}) ' set M1' \cup set-mset (init-clss S) \models_p D + \{\#L\# \}$  by auto
  have  $atms-of (D + \{\#L\# \}) \subseteq atms-of-msu (clauses S)$ 
    using alien conf unfolding no-strange-atm-def clauses-def by auto
  then have  $(\lambda a. \{\#lit-of a\# \}) ' set M1' \cup set-mset (init-clss S) \models_p \{\#L\# \}$ 
    using true-clss-clss-plus-CNot[OF  $T' TT$ ] by auto
ultimately
  have case  $x$  of ( $Ls, seen$ )  $\Rightarrow (\lambda a. \{\#lit-of a\# \}) ' set Ls$ 
     $\cup set-mset (init-clss T)$ 
     $\models_{ps} (\lambda a. \{\#lit-of a\# \}) ' set seen$  using  $T' T decomp' undef inv$  unfolding  $x'$ 
    by (simp add: cdclW-M-level-inv-decomp)
}
ultimately show case  $x$  of ( $Ls, seen$ )  $\Rightarrow (\lambda a. \{\#lit-of a\# \}) ' set Ls \cup set-mset (init-clss T)$ 
   $\models_{ps} (\lambda a. \{\#lit-of a\# \}) ' set seen$  using  $T$  by auto
qed
qed

```

lemma *cdcl_W-propagate-is-false:*

assumes

cdcl_W S S' and

lev: cdcl_W-M-level-inv S and

learned: $cdcl_W$ -learned-clause S **and**
decomp: all-decomposition-implies- m ($init_class\ S$) ($get_all_marked_decomposition\ (trail\ S)$) **and**
confl: $\forall T.$ conflicting $S = C$ -Clause $T \longrightarrow trail\ S \models_{as} CNot\ T$ **and**
alien: no-strange-atm S **and**
mark-confl: every-mark-is-a-conflict S
shows every-mark-is-a-conflict S'
using $assms(1,2)$
proof (*induct rule*: $cdcl_W$ -all-induct-lev2)
case ($propagate\ C\ L\ T$) **note** $undef = this(3)$ **and** $T = this(5)$
show ?case
proof (*intro allI impI*)
fix L' mark $a\ b$
assume $a @ Propagated\ L'\ mark\ \# b = trail\ T$
then have $(a = [] \wedge L = L' \wedge mark = C + \{\#L\# \} \wedge b = trail\ S)$
 $\vee tl\ a @ Propagated\ L'\ mark\ \# b = trail\ S$
using $T\ undef$ **by** ($cases\ a$) *fastforce*+
moreover {
assume $tl\ a @ Propagated\ L'\ mark\ \# b = trail\ S$
then have $b \models_{as} CNot\ (mark - \{\#L'\#\}) \wedge L' \in \# mark$
using *mark-confl* **by** *auto*
}
moreover {
assume $a = []$ **and** $L = L'$ **and** $mark = C + \{\#L\#\}$ **and** $b = trail\ S$
then have $b \models_{as} CNot\ (mark - \{\#L\#\}) \wedge L \in \# mark$
using $\langle trail\ S \models_{as} CNot\ C \rangle$ **by** *auto*
}
ultimately show $b \models_{as} CNot\ (mark - \{\#L'\#\}) \wedge L' \in \# mark$ **by** *blast*
qed
next
case ($decide\ L$) **note** $undef[simp] = this(2)$ **and** $T = this(4)$
have $\bigwedge a\ La\ mark\ b. a @ Propagated\ La\ mark\ \# b = Marked\ L\ (backtrack_lvl\ S + 1) \# trail\ S$
 $\implies tl\ a @ Propagated\ La\ mark\ \# b = trail\ S$ **by** ($case_tac\ a, auto$)
then show ?case **using** *mark-confl* T **unfolding** $decide.hyps(1)$ **by** *fastforce*
next
case ($skip\ L\ C'\ M\ D\ T$) **note** $tr = this(1)$ **and** $T = this(5)$
show ?case
proof (*intro allI impI*)
fix L' mark $a\ b$
assume $a @ Propagated\ L'\ mark\ \# b = trail\ T$
then have $a @ Propagated\ L'\ mark\ \# b = M$ **using** $tr\ T$ **by** *simp*
then have $(Propagated\ L\ C' \# a) @ Propagated\ L'\ mark\ \# b = Propagated\ L\ C' \# M$ **by** *auto*
moreover have $\forall La\ mark\ a\ b. a @ Propagated\ La\ mark\ \# b = Propagated\ L\ C' \# M$
 $\longrightarrow b \models_{as} CNot\ (mark - \{\#La\#\}) \wedge La \in \# mark$
using *mark-confl* **unfolding** $skip.hyps(1)$ **by** *simp*
ultimately show $b \models_{as} CNot\ (mark - \{\#L'\#\}) \wedge L' \in \# mark$ **by** *blast*
qed
next
case (*conflict* D)
then show ?case **using** *mark-confl* **by** *simp*
next
case ($resolve\ L\ C\ M\ D\ T$) **note** $tr-S = this(1)$ **and** $T = this(4)$
show ?case **unfolding** $resolve.hyps(1)$
proof (*intro allI impI*)
fix L' mark $a\ b$
assume $a @ Propagated\ L'\ mark\ \# b = trail\ T$

```

    then have Propagated  $L \ ( \ (C + \{\#L\# \}) ) \# M$ 
      = (Propagated  $L \ ( \ (C + \{\#L\# \}) ) \# a$ ) @ Propagated  $L' \text{ mark} \# b$ 
    using T tr-S by auto
    then show  $b \models_{as} CNot \ ( \text{mark} - \{\#L'\# \} ) \wedge L' \in \# \text{ mark}$ 
      using mark-confl unfolding resolve.hyps(1) by presburger
  qed
next
case restart
  then show ?case by auto
next
case forget
  then show ?case using mark-confl by auto
next
case (backtrack  $K \ i \ M1 \ M2 \ L \ D \ T$ ) note decomp = this(1) and conf = this(3) and undef = this(6)
and
   $T = this(7)$ 
  have  $\forall l \in \text{set } M2. \neg \text{is-marked } l$ 
    using get-all-marked-decomposition-snd-not-marked backtrack.hyps(1) by blast
  obtain  $M0$  where  $M: \text{trail } S = M0 \ @ \ M2 \ @ \ \text{Marked } K \ (i + 1) \# M1$ 
    using backtrack.hyps(1) by auto
  have [simp]:  $\text{trail } (\text{reduce-trail-to } M1 \ (\text{add-learned-cls } (D + \{\#L\# \})$ 
    (update-backtrack-lvl  $i \ (\text{update-conflicting } C\text{-True } S))) = M1$ 
    using decomp lev by (auto simp: cdclW-M-level-inv-decomp)
  show ?case
  proof (intro allI impI)
    fix  $La \text{ mark } a \ b$ 
    assume  $a \ @ \ \text{Propagated } La \text{ mark} \# b = \text{trail } T$ 
    then have  $(a = [] \wedge \text{Propagated } La \text{ mark} = \text{Propagated } L \ (D + \{\#L\# \}) \wedge b = M1)$ 
       $\vee tl \ a \ @ \ \text{Propagated } La \text{ mark} \# b = M1$ 
      using  $M \ T \text{ decomp undef}$  by (cases a) (auto)
    moreover {
      assume  $A: a = []$  and
         $P: \text{Propagated } La \text{ mark} = \text{Propagated } L \ ( \ (D + \{\#L\# \}) )$  and
         $b: b = M1$ 
      have  $\text{trail } S \models_{as} CNot \ D$  using conf confl by auto
      then have  $\text{vars-of-} D: \text{atms-of } D \subseteq \text{atm-of } \text{'lits-of } (\text{trail } S)$ 
        unfolding atms-of-def
        by (meson image-subsetI mem-set-mset-iff true-annots-CNot-all-atms-defined)
      have  $\text{vars-of-} D: \text{atms-of } D \subseteq \text{atm-of } \text{'lits-of } M1$ 
        using backtrack-atms-of-D-in-M1[of S M1 L D i K M2 T] T backtrack lev confl by auto
      have no-dup (trail S) using lev by (auto simp: cdclW-M-level-inv-decomp)
      then have  $\text{vars-in-} M1: \forall x \in \text{atms-of } D. x \notin$ 
         $\text{atm-of } \text{'lits-of } (M0 \ @ \ M2 \ @ \ \text{Marked } K \ (i + 1) \# [])$ 
        using vars-of-D distinct-atms-of-incl-not-in-other[of M0 @ M2 @ Marked K (i + 1) # [] M1]
        unfolding M by auto
      have  $M1 \models_{as} CNot \ D$ 
        using vars-in-M1 true-annots-remove-if-notin-vars[of M0 @ M2 @ Marked K (i + 1) # [] M1
          CNot D] (trail S  $\models_{as} CNot \ D$ ) unfolding M lits-of-def by simp
      then have  $b \models_{as} CNot \ ( \text{mark} - \{\#La\# \} ) \wedge La \in \# \text{ mark}$ 
        using P b by auto
    }
  moreover {
    assume  $tl \ a \ @ \ \text{Propagated } La \text{ mark} \# b = M1$ 
    then obtain  $c'$  where  $c' \ @ \ \text{Propagated } La \text{ mark} \# b = \text{trail } S$  unfolding M by auto
    then have  $b \models_{as} CNot \ ( \text{mark} - \{\#La\# \} ) \wedge La \in \# \text{ mark}$ 

```

```

    using mark-confl by blast
  }
  ultimately show  $b \models_{as} CNot (mark - \{\#La\# \}) \wedge La \in \# \text{ mark}$  by fast
qed
qed

lemma cdclW-conflicting-is-false:
  assumes
    cdclW S S' and
    M-lev: cdclW-M-level-inv S and
    confl-inv:  $\forall T. \text{conflicting } S = C\text{-Clause } T \longrightarrow \text{trail } S \models_{as} CNot T$  and
    marked-confl:  $\forall L \text{ mark } a b. a @ \text{Propagated } L \text{ mark } \# b = (\text{trail } S)$ 
     $\longrightarrow (b \models_{as} CNot (mark - \{\#L\# \}) \wedge L \in \# \text{ mark})$  and
    dist: distinct-cdclW-state S
  shows  $\forall T. \text{conflicting } S' = C\text{-Clause } T \longrightarrow \text{trail } S' \models_{as} CNot T$ 
  using assms(1,2)
proof (induct rule: cdclW-all-induct-lev2)
  case (skip L C' M D) note tr-S = this(1) and T = this(5)
  then have Propagated L C' # M  $\models_{as} CNot D$  using assms skip by auto
  moreover
    have  $L \notin \# D$ 
    proof (rule ccontr)
      assume  $\neg ?thesis$ 
      then have  $-L \in \text{lits-of } M$ 
      using in-CNot-implies-uminus(2)[of D L Propagated L C' # M]
       $\langle \text{Propagated } L C' \# M \models_{as} CNot D \rangle$  by simp
      then show False
      by (metis M-lev cdclW-M-level-inv-decomp(1) consistent-interp-def insert-iff
        lits-of-cons marked-lit.sel(2) skip.hyps(1))
    qed
  ultimately show ?case
    using skip.hyps(1-3) true-annots-CNot-lit-of-notin-skip T unfolding cdclW-M-level-inv-def
    by fastforce
next
  case (resolve L C M D T) note tr = this(1) and confl = this(2) and T = this(4)
  show ?case
    proof (intro allI impI)
      fix T'
      have  $\text{tl } (\text{trail } S) \models_{as} CNot C$  using tr assms(4) by fastforce
      moreover
        have distinct-mset (D + {\#- L\#}) using confl dist
        unfolding distinct-cdclW-state-def by auto
        then have  $-L \notin \# D$  unfolding distinct-mset-def by auto
        have  $M \models_{as} CNot D$ 
        proof -
          have Propagated L ( (C + {\#L\#}) ) # M  $\models_{as} CNot D \cup CNot \{\#- L\# \}$ 
          using confl tr confl-inv by force
          then show ?thesis
          using M-lev  $\langle -L \notin \# D \rangle$  tr true-annots-lit-of-notin-skip
          unfolding cdclW-M-level-inv-def by force
        qed
      qed
    moreover assume conflicting T = C-Clause T'
    ultimately
      show  $\text{trail } T \models_{as} CNot T'$ 
      using tr T by auto

```

qed
 qed (auto simp: assms(2) cdcl_W-M-level-inv-decomp)

lemma cdcl_W-conflicting-decomp:
 assumes cdcl_W-conflicting S
 shows $\forall T. \text{conflicting } S = C\text{-Clause } T \longrightarrow \text{trail } S \models_{as} CNot \ T$
 and $\forall L \text{ mark } a \ b. a \ @ \ \text{Propagated } L \ \text{mark } \# \ b = (\text{trail } S)$
 $\longrightarrow (b \models_{as} CNot \ (\text{mark} - \{\#L\}) \wedge L \in \# \ \text{mark})$
 using assms **unfolding** cdcl_W-conflicting-def **by** blast+

lemma cdcl_W-conflicting-decomp2:
 assumes cdcl_W-conflicting S and conflicting $S = C\text{-Clause } T$
 shows $\text{trail } S \models_{as} CNot \ T$
 using assms **unfolding** cdcl_W-conflicting-def **by** blast+

lemma cdcl_W-conflicting-decomp2':
 assumes
 cdcl_W-conflicting S and
 conflicting $S = C\text{-Clause } D$
 shows $\text{trail } S \models_{as} CNot \ D$
 using assms **unfolding** cdcl_W-conflicting-def **by** auto

lemma cdcl_W-conflicting-S0-cdcl_W[simp]:
 cdcl_W-conflicting (init-state N)
unfolding cdcl_W-conflicting-def **by** auto

17.4.9 Putting all the invariants together

lemma cdcl_W-all-inv:
 assumes cdcl_W: cdcl_W $S \ S'$ and
 1: all-decomposition-implies-m (init-clss S) (get-all-marked-decomposition (trail S)) and
 2: cdcl_W-learned-clause S and
 4: cdcl_W-M-level-inv S and
 5: no-strange-atm S and
 7: distinct-cdcl_W-state S and
 8: cdcl_W-conflicting S
 shows all-decomposition-implies-m (init-clss S') (get-all-marked-decomposition (trail S'))
 and cdcl_W-learned-clause S'
 and cdcl_W-M-level-inv S'
 and no-strange-atm S'
 and distinct-cdcl_W-state S'
 and cdcl_W-conflicting S'
proof –
 show $S1$: all-decomposition-implies-m (init-clss S') (get-all-marked-decomposition (trail S'))
 using cdcl_W-propagate-is-conclusion[OF cdcl_W 4 1 2 - 5] 8 **unfolding** cdcl_W-conflicting-def
by blast
 show $S2$: cdcl_W-learned-clause S' **using** cdcl_W-learned-clss[OF cdcl_W 2 4] .
 show $S4$: cdcl_W-M-level-inv S' **using** cdcl_W-consistent-inv[OF cdcl_W 4] .
 show $S5$: no-strange-atm S' **using** cdcl_W-no-strange-atm-inv[OF cdcl_W 5 4] .
 show $S7$: distinct-cdcl_W-state S' **using** distinct-cdcl_W-state-inv[OF cdcl_W 4 7] .
 show $S8$: cdcl_W-conflicting S'
 using cdcl_W-conflicting-is-false[OF cdcl_W 4 - - 7] 8 cdcl_W-propagate-is-false[OF cdcl_W 4 2 1 - 5]
unfolding cdcl_W-conflicting-def **by** fast
 qed

lemma *rtrancpl-cdcl_W-all-inv*:

assumes

cdcl_W: *rtrancpl cdcl_W S S'* and

1: *all-decomposition-implies-m* (*init-clss S*) (*get-all-marked-decomposition* (*trail S*)) and

2: *cdcl_W-learned-clause S* and

4: *cdcl_W-M-level-inv S* and

5: *no-strange-atm S* and

7: *distinct-cdcl_W-state S* and

8: *cdcl_W-conflicting S*

shows

all-decomposition-implies-m (*init-clss S'*) (*get-all-marked-decomposition* (*trail S'*)) and

cdcl_W-learned-clause S' and

cdcl_W-M-level-inv S' and

no-strange-atm S' and

distinct-cdcl_W-state S' and

cdcl_W-conflicting S'

using *assms*

proof (*induct rule: rtrancpl-induct*)

case *base*

case 1 **then show** ?*case* **by** *blast*

case 2 **then show** ?*case* **by** *blast*

case 3 **then show** ?*case* **by** *blast*

case 4 **then show** ?*case* **by** *blast*

case 5 **then show** ?*case* **by** *blast*

case 6 **then show** ?*case* **by** *blast*

next

case (*step S' S''*) **note** *H = this*

case 1 **with** *H(3-7)[OF this(1-6)]* **show** ?*case* **using** *cdcl_W-all-inv[OF H(2)]*

H **by** *presburger*

case 2 **with** *H(3-7)[OF this(1-6)]* **show** ?*case* **using** *cdcl_W-all-inv[OF H(2)]*

H **by** *presburger*

case 3 **with** *H(3-7)[OF this(1-6)]* **show** ?*case* **using** *cdcl_W-all-inv[OF H(2)]*

H **by** *presburger*

case 4 **with** *H(3-7)[OF this(1-6)]* **show** ?*case* **using** *cdcl_W-all-inv[OF H(2)]*

H **by** *presburger*

case 5 **with** *H(3-7)[OF this(1-6)]* **show** ?*case* **using** *cdcl_W-all-inv[OF H(2)]*

H **by** *presburger*

case 6 **with** *H(3-7)[OF this(1-6)]* **show** ?*case* **using** *cdcl_W-all-inv[OF H(2)]*

H **by** *presburger*

qed

lemma *all-invariant-S0-cdcl_W*:

assumes *distinct-mset-mset N*

shows *all-decomposition-implies-m* (*init-clss* (*init-state N*))

(*get-all-marked-decomposition* (*trail* (*init-state N*))))

and *cdcl_W-learned-clause* (*init-state N*)

and $\forall T. \text{conflicting}(\text{init-state } N) = C\text{-Clause } T \longrightarrow (\text{trail}(\text{init-state } N)) \models_{as} C\text{Not } T$

and *no-strange-atm* (*init-state N*)

and *consistent-interp* (*lits-of* (*trail* (*init-state N*))))

and $\forall L \text{ mark } a \text{ b. } a @ \text{Propagated } L \text{ mark } \# \text{ b} = \text{trail}(\text{init-state } N) \longrightarrow$

($b \models_{as} C\text{Not}(\text{mark} - \{\#L\}) \wedge L \in \# \text{ mark}$)

and *distinct-cdcl_W-state* (*init-state N*)

using *assms* **by** *auto*

lemma *cdcl_W-only-propagated-vars-unsat*:

assumes

marked: $\forall x \in \text{set } M. \neg \text{is-marked } x$ **and**

DN: $D \in \# \text{ clauses } S$ **and**

D: $M \models_{as} CNot\ D$ **and**

inv: *all-decomposition-implies-m* *N* (*get-all-marked-decomposition* *M*) **and**

state: *state* *S* = (*M*, *N*, *U*, *k*, *C*) **and**

learned-cl: *cdcl_W-learned-clause* *S* **and**

atm-incl: *no-strange-atm* *S*

shows *unsatisfiable* (*set-mset* *N*)

proof (*rule ccontr*)

assume $\neg \text{unsatisfiable} (\text{set-mset } N)$

then obtain *I* **where**

I: $I \models_s \text{set-mset } N$ **and**

cons: *consistent-interp* *I* **and**

tot: *total-over-m* *I* (*set-mset* *N*)

unfolding *satisfiable-def* **by** *auto*

have *atms-of-msu* $N \cup \text{atms-of-msu } U = \text{atms-of-msu } N$

using *atm-incl* *state* **unfolding** *total-over-m-def* *no-strange-atm-def*

by (*auto simp add: clauses-def*)

then have *total-over-m* *I* (*set-mset* *N*) **using** *tot* **unfolding** *total-over-m-def* **by** *auto*

moreover have $N \models_{psm} U$ **using** *learned-cl* *state* **unfolding** *cdcl_W-learned-clause-def* **by** *auto*

ultimately have *I-D*: $I \models D$

using *I DN cons state* **unfolding** *true-clss-clss-def* *true-clss-def* *Ball-def*

by (*metis Un-iff* $\langle \text{atms-of-msu } N \cup \text{atms-of-msu } U = \text{atms-of-msu } N \rangle$ *atms-of-ms-union* *clauses-def*

mem-set-mset-iff *prod.inject* *set-mset-union* *total-over-m-def*)

have *l0*: $\{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\} = \{\}$ **using** *marked* **by** *auto*

have *atms-of-ms* (*set-mset* $N \cup (\lambda a. \{\#lit\text{-of } a\# \}) \text{ 'set } M$) = *atms-of-msu* *N*

using *atm-incl* *state* **unfolding** *no-strange-atm-def* **by** *auto*

then have *total-over-m* *I* (*set-mset* $N \cup (\lambda a. \{\#lit\text{-of } a\# \}) \text{ 'set } M$)

using *tot* **unfolding** *total-over-m-def* **by** *auto*

then have $I \models_s (\lambda a. \{\#lit\text{-of } a\# \}) \text{ 'set } M$

using *all-decomposition-implies-propagated-lits-are-implied*[*OF inv*] *cons I*

unfolding *true-clss-clss-def* *l0* **by** *auto*

then have *IM*: $I \models_s (\lambda a. \{\#lit\text{-of } a\# \}) \text{ 'set } M$ **by** *auto*

{

fix *K*

assume $K \in \# D$

then have $-K \in \text{lits-of } M$

using *D* **unfolding** *true-annots-def* *Ball-def* *CNot-def* *true-annot-def* *true-cls-def* *true-lit-def*

Bex-mset-def **by** (*metis* (*mono-tags*, *lifting*) *count-single* *less-not-refl* *mem-Collect-eq*)

then have $-K \in I$ **using** *IM* *true-clss-singleton-lit-of-implies-incl* *lits-of-def* **by** *fastforce*

}

then have $\neg I \models D$ **using** *cons* **unfolding** *true-cls-def* *true-lit-def* *consistent-interp-def* **by** *auto*

then show *False* **using** *I-D* **by** *blast*

qed

We have actually a much stronger theorem, namely *all-decomposition-implies ?N* (*get-all-marked-decomposition* *?M*) $\implies ?N \cup \{\{\#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } ?M\} \models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ 'set } ?M$, that show that the only choices we made are marked in the formula

lemma

assumes *all-decomposition-implies-m* *N* (*get-all-marked-decomposition* *M*)

and $\forall m \in \text{set } M. \neg \text{is-marked } m$

shows *set-mset* *N* $\models_{ps} (\lambda a. \{\#lit\text{-of } a\# \}) \text{ 'set } M$

proof –
 have $T: \{\{\#lit\text{-of } L\# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M\} = \{\}$ **using** *assms*(2) **by** *auto*
 then show *?thesis*
 using *all-decomposition-implies-propagated-lits-are-implied*[*OF assms*(1)] **unfolding** *T* **by** *simp*
qed

lemma *conflict-with-false-implies-unsat*:

assumes
cdcl_W: *cdcl_W S S'* **and**
lev: *cdcl_W-M-level-inv S* **and**
[simp]: *conflicting S' = C-Clause {#}* **and**
learned: *cdcl_W-learned-clause S*
shows *unsatisfiable (set-mset (init-clss S))*
using *assms*

proof –

have *cdcl_W-learned-clause S'* **using** *cdcl_W-learned-clss cdcl_W learned lev* **by** *auto*
 then have *init-clss S' \models_{pm} {#}* **using** *assms*(3) **unfolding** *cdcl_W-learned-clause-def* **by** *auto*
 then have *init-clss S \models_{pm} {#}*
 using *cdcl_W-init-clss*[*OF assms*(1) *lev*] **by** *auto*
 then show *?thesis* **unfolding** *satisfiable-def true-clss-clss-def* **by** *auto*
qed

lemma *conflict-with-false-implies-terminated*:

assumes *cdcl_W S S'*
and *conflicting S = C-Clause {#}*
shows *False*
using *assms* **by** (*induct rule: cdcl_W-all-induct*) *auto*

17.4.10 No tautology is learned

This is a simple consequence of all we have shown previously. It is not strictly necessary, but helps finding a better bound on the number of learned clauses.

lemma *learned-clss-are-not-tautologies*:

assumes
cdcl_W S S' **and**
lev: *cdcl_W-M-level-inv S* **and**
conflicting: *cdcl_W-conflicting S* **and**
no-tauto: $\forall s \in \# \text{ learned-clss } S. \neg \text{tautology } s$
shows $\forall s \in \# \text{ learned-clss } S'. \neg \text{tautology } s$
using *assms*

proof (*induct rule: cdcl_W-all-induct-lev2*)

case (*backtrack K i M1 M2 L D*) **note** *confl = this*(3)
 have *consistent-interp (lits-of (trail S))* **using** *lev* **by** (*auto simp: cdcl_W-M-level-inv-decomp*)
moreover
 have *trail S \models_{as} CNot (D + {#L#})*
 using *conflicting confl* **unfolding** *cdcl_W-conflicting-def* **by** *auto*
 then have *lits-of (trail S) \models_s CNot (D + {#L#})* **using** *true-annots-true-clss* **by** *blast*
 ultimately have $\neg \text{tautology } (D + \{ \#L\# \})$ **using** *consistent-CNot-not-tautology* **by** *blast*
 then show *?case* **using** *backtrack no-tauto*
 by (*auto simp: cdcl_W-M-level-inv-decomp split: split-if-asm*)

next

case *restart*

then show *?case* **using** *learned-clss-restart-state state-eq-learned-clss no-tauto*
 by (*metis (no-types, lifting) ball-msetE ball-msetI mem-set-mset-iff set-mset-mono subsetCE*)

qed *auto*

definition *final-cdcl_W-state* (*S*:: 'st)
 \longleftrightarrow (*trail S* \models_{asm} *init-clss S*
 $\vee ((\forall L \in \text{set } (\text{trail } S). \neg \text{is-marked } L) \wedge$
 $(\exists C \in \# \text{ init-clss } S. \text{trail } S \models_{as} C \text{Not } C)))$

definition *termination-cdcl_W-state* (*S*:: 'st)
 \longleftrightarrow (*trail S* \models_{asm} *init-clss S*
 $\vee ((\forall L \in \text{atms-of-msu } (\text{init-clss } S). L \in \text{atm-of ' lits-of } (\text{trail } S))$
 $\wedge (\exists C \in \# \text{ init-clss } S. \text{trail } S \models_{as} C \text{Not } C)))$

17.5 CDCL Strong Completeness

fun *mapi* :: ('a \Rightarrow nat \Rightarrow 'b) \Rightarrow nat \Rightarrow 'a list \Rightarrow 'b list **where**
mapi - - [] = [] |
mapi *f* *n* (*x* # *xs*) = *f* *x* *n* # *mapi* *f* (*n* - 1) *xs*

lemma *mark-not-in-set-mapi[simp]*: $L \notin \text{set } M \implies \text{Marked } L \ k \notin \text{set } (\text{mapi } \text{Marked } i \ M)$
by (*induct* *M* *arbitrary*: *i*) *auto*

lemma *propagated-not-in-set-mapi[simp]*: $L \notin \text{set } M \implies \text{Propagated } L \ k \notin \text{set } (\text{mapi } \text{Marked } i \ M)$
by (*induct* *M* *arbitrary*: *i*) *auto*

lemma *image-set-mapi*:
 $f \text{ ' set } (\text{mapi } g \ i \ M) = \text{set } (\text{mapi } (\lambda x \ i. f \ (g \ x \ i)) \ i \ M)$
by (*induction* *M* *arbitrary*: *i*) *auto*

lemma *mapi-map-convert*:
 $\forall x \ i \ j. f \ x \ i = f \ x \ j \implies \text{mapi } f \ i \ M = \text{map } (\lambda x. f \ x \ 0) \ M$
by (*induction* *M* *arbitrary*: *i*) *auto*

lemma *defined-lit-mapi*: $\text{defined-lit } (\text{mapi } \text{Marked } i \ M) \ L \longleftrightarrow \text{atm-of } L \in \text{atm-of ' set } M$
by (*induction* *M*) (*auto simp: defined-lit-map image-set-mapi mapi-map-convert*)

lemma *cdcl_W-can-do-step*:
assumes
consistent-interp (*set M*) **and**
distinct *M* **and**
 $\text{atm-of ' } (\text{set } M) \subseteq \text{atms-of-msu } N$
shows $\exists S. \text{rtranclp } \text{cdcl}_W \ (\text{init-state } N) \ S$
 $\wedge \text{state } S = (\text{mapi } \text{Marked } (\text{length } M) \ M, N, \{\#\}, \text{length } M, C\text{-True})$
using *assms*
proof (*induct* *M*)
case *Nil*
then show ?*case* **by** *auto*
next
case (*Cons L M*) **note** *IH* = *this*(1)
have *consistent-interp* (*set M*) **and** *distinct* *M* **and** $\text{atm-of ' set } M \subseteq \text{atms-of-msu } N$
using *Cons.prem*(1-3) **unfolding** *consistent-interp-def* **by** *auto*
then obtain *S* **where**
 $\text{st: } \text{cdcl}_W^{**} \ (\text{init-state } N) \ S$ **and**
 $S: \text{state } S = (\text{mapi } \text{Marked } (\text{length } M) \ M, N, \{\#\}, \text{length } M, C\text{-True})$
using *IH* **by** *auto*
let ?*S*₀ = *incr-lvl* (*cons-trail* (*Marked L* (*length M* + 1)) *S*)
have *undefined-lit* (*mapi* *Marked* (*length M*) *M*) *L*


```

    using Cons.premis(1,2) unfolding defined-lit-def consistent-interp-def by fastforce
  moreover have init-cls S = N
    using S by blast
  moreover have atm-of L ∈ atms-of-msu N using Cons.premis(3) by auto
  moreover have undef: undefined-lit (trail S) L
    using S ⟨distinct (L#M)⟩ calculation(1) by (auto simp: defined-lit-mapi defined-lit-map)
  ultimately have cdclW S ?S0
    using cdclW.other[OF cdclW-o.decide[OF decide-rule[OF S,
      of L ?S0]]] S by (auto simp: state-eq-def simp del: state-simp)
  then show ?case
    using st S undef by (auto intro!: exI[of - ?S0])
qed

```

lemma *cdcl_W-strong-completeness*:

```

  assumes
    set M ⊨s set-mset N and
    consistent-interp (set M) and
    distinct M and
    atm-of ' (set M) ⊆ atms-of-msu N
  obtains S where
    state S = (mapi Marked (length M) M, N, {#}, length M, C-True) and
    rtranclp cdclW (init-state N) S and
    final-cdclW-state S
proof -
  obtain S where
    st: rtranclp cdclW (init-state N) S and
    S: state S = (mapi Marked (length M) M, N, {#}, length M, C-True)
  using cdclW-can-do-step[OF assms(2-4)] by auto
  have lits-of (mapi Marked (length M) M) = set M
    by (induct M, auto)
  then have mapi Marked (length M) M ⊨asm N using assms(1) true-annots-true-cls by metis
  then have final-cdclW-state S
    using S unfolding final-cdclW-state-def by auto
  then show ?thesis using that st S by blast
qed

```

17.6 Higher level strategy

The rules described previously do not lead to a conclusive state. We have to add a strategy.

17.6.1 Definition

lemma *tranclp-conflict-iff*[*iff*]:

full1 conflict S S' ⟷ conflict S S'

proof –

```

  have tranclp conflict S S' ⟹ conflict S S'
    unfolding full1-def by (induct rule: tranclp.induct) force+
  then have tranclp conflict S S' ⟹ conflict S S' by (meson rtranclpD)
  then show ?thesis unfolding full1-def by (metis conflictE conflicting-clause.simps(3)
    conflicting-update-conflicting state-eq-conflicting tranclp.intros(1))
qed

```

inductive *cdcl_W-cp* :: 'st ⇒ 'st ⇒ bool **where**
conflict '[*intro*]: *conflict S S' ⟹ cdcl_W-cp S S' |*
propagate': *propagate S S' ⟹ cdcl_W-cp S S'*

```

lemma rtrancp-cdclW-cp-rtrancp-cdclW:
  cdclW-cp** S T  $\implies$  cdclW** S T
  by (induction rule: rtrancp-induct) (auto simp: cdclW-cp.simps dest: cdclW.intros)

lemma cdclW-cp-state-eq-compatible:
  assumes
    cdclW-cp S T and
    S  $\sim$  S' and
    T  $\sim$  T'
  shows cdclW-cp S' T'
  using assms
  apply (induction)
    using conflict-state-eq-compatible apply auto[1]
  using propagate' propagate-state-eq-compatible by auto

lemma trancp-cdclW-cp-state-eq-compatible:
  assumes
    cdclW-cp++ S T and
    S  $\sim$  S' and
    T  $\sim$  T'
  shows cdclW-cp++ S' T'
  using assms
proof induction
  case base
  then show ?case
    using cdclW-cp-state-eq-compatible by blast
next
  case (step U V)
  obtain ss :: 'st where
    cdclW-cp S ss  $\wedge$  cdclW-cp** ss U
  by (metis (no-types) step(1) trancpD)
  then show ?case
    by (meson cdclW-cp-state-eq-compatible rtrancp.rtrancp-into-rtrancp rtrancp-into-trancp2
      state-eq-ref step(2) step(4) step(5))
qed

lemma conflicting-clause-full-cdclW-cp:
  conflicting S  $\neq$  C-True  $\implies$  full cdclW-cp S S
unfolding full-def rtrancp-unfold trancp-unfold by (auto simp add: cdclW-cp.simps)

lemma skip-unique:
  skip S T  $\implies$  skip S T'  $\implies$  T  $\sim$  T'
  by (fastforce simp: state-eq-def simp del: state-simp)

lemma resolve-unique:
  resolve S T  $\implies$  resolve S T'  $\implies$  T  $\sim$  T'
  by (fastforce simp: state-eq-def simp del: state-simp)

lemma cdclW-cp-no-more-clauses:
  assumes cdclW-cp S S'
  shows clauses S = clauses S'
  using assms by (induct rule: cdclW-cp.induct) (auto elim!: conflictE propagateE)

lemma trancp-cdclW-cp-no-more-clauses:

```

assumes $cdcl_W\text{-cp}^{++} S S'$
shows $clauses S = clauses S'$
using *assms* **by** (*induct rule*: *trancpl.induct*) (*auto dest*: *cdcl_W-cp-no-more-clauses*)

lemma *rtrancpl-cdcl_W-cp-no-more-clauses*:

assumes $cdcl_W\text{-cp}^{**} S S'$
shows $clauses S = clauses S'$
using *assms* **by** (*induct rule*: *rtrancpl.induct*) (*fastforce dest*: *cdcl_W-cp-no-more-clauses*)⁺

lemma *no-conflict-after-conflict*:

$conflict S T \implies \neg conflict T U$
by *fastforce*

lemma *no-propagate-after-conflict*:

$conflict S T \implies \neg propagate T U$
by *fastforce*

lemma *trancpl-cdcl_W-cp-propagate-with-conflict-or-not*:

assumes $cdcl_W\text{-cp}^{++} S U$
shows ($propagate^{++} S U \wedge conflicting U = C\text{-True}$)
 $\vee (\exists T D. propagate^{**} S T \wedge conflict T U \wedge conflicting U = C\text{-Clause } D)$

proof –

have $propagate^{++} S U \vee (\exists T. propagate^{**} S T \wedge conflict T U)$
using *assms* **by** *induction*
(*force simp*: *cdcl_W-cp.simps* *trancpl-into-rtrancpl* *dest*: *no-conflict-after-conflict*
no-propagate-after-conflict)⁺

moreover

have $propagate^{++} S U \implies conflicting U = C\text{-True}$
unfolding *trancpl-unfold-end* **by** *auto*

moreover

have $\bigwedge T. conflict T U \implies \exists D. conflicting U = C\text{-Clause } D$
by *auto*

ultimately show *?thesis* **by** *meson*

qed

lemma *cdcl_W-cp-conflicting-not-empty[simp]*: $conflicting S = C\text{-Clause } D \implies \neg cdcl_W\text{-cp } S S'$

proof

assume $cdcl_W\text{-cp } S S'$ **and** $conflicting S = C\text{-Clause } D$
then show *False* **by** (*induct rule*: *cdcl_W-cp.induct*) *auto*

qed

lemma *no-step-cdcl_W-cp-no-conflict-no-propagate*:

assumes *no-step cdcl_W-cp S*
shows *no-step conflict S* **and** *no-step propagate S*
using *assms* *conflict'* **apply** *blast*
by (*meson* *assms* *conflict'* *propagate'*)

CDCL with the reasonable strategy: we fully propagate the conflict and propagate, then we apply any other possible rule *cdcl_W-o S S'* and re-apply conflict and propagate *full cdcl_W-cp S' S''*

inductive *cdcl_W-stgy* :: *'st* \Rightarrow *'st* \Rightarrow *bool* **for** *S* :: *'st* **where**

conflict': *full1 cdcl_W-cp S S'* \implies *cdcl_W-stgy S S'* |

other': *cdcl_W-o S S'* \implies *no-step cdcl_W-cp S* \implies *full cdcl_W-cp S' S''* \implies *cdcl_W-stgy S S''*

17.6.2 Invariants

These are the same invariants as before, but lifted

lemma *cdcl_W-cp-learned-clause-inv*:

assumes *cdcl_W-cp* *S S'*

shows *learned-clss S = learned-clss S'*

using *assms* **by** (*induct* rule: *cdcl_W-cp.induct*) *fastforce*+

lemma *rtrancpl-cdcl_W-cp-learned-clause-inv*:

assumes *cdcl_W-cp^{**}* *S S'*

shows *learned-clss S = learned-clss S'*

using *assms* **by** (*induct* rule: *rtrancpl-induct*) (*fastforce* dest: *cdcl_W-cp-learned-clause-inv*)+

lemma *trancpl-cdcl_W-cp-learned-clause-inv*:

assumes *cdcl_W-cp⁺⁺* *S S'*

shows *learned-clss S = learned-clss S'*

using *assms* **by** (*simp* add: *rtrancpl-cdcl_W-cp-learned-clause-inv* *trancpl-into-rtrancpl*)

lemma *cdcl_W-cp-backtrack-lvl*:

assumes *cdcl_W-cp* *S S'*

shows *backtrack-lvl S = backtrack-lvl S'*

using *assms* **by** (*induct* rule: *cdcl_W-cp.induct*) *fastforce*+

lemma *rtrancpl-cdcl_W-cp-backtrack-lvl*:

assumes *cdcl_W-cp^{**}* *S S'*

shows *backtrack-lvl S = backtrack-lvl S'*

using *assms* **by** (*induct* rule: *rtrancpl-induct*) (*fastforce* dest: *cdcl_W-cp-backtrack-lvl*)+

lemma *cdcl_W-cp-consistent-inv*:

assumes *cdcl_W-cp* *S S'*

and *cdcl_W-M-level-inv* *S*

shows *cdcl_W-M-level-inv* *S'*

using *assms*

proof (*induct* rule: *cdcl_W-cp.induct*)

case (*conflict'*)

then show ?*case* **using** *cdcl_W-consistent-inv* *cdcl_W.conflict* **by** *blast*

next

case (*propagate' S S'*)

have *cdcl_W* *S S'*

using *propagate'.hyps*(1) *propagate* **by** *blast*

then show *cdcl_W-M-level-inv* *S'*

using *propagate'.prems*(1) *cdcl_W-consistent-inv* *propagate* **by** *blast*

qed

lemma *full1-cdcl_W-cp-consistent-inv*:

assumes *full1 cdcl_W-cp* *S S'*

and *cdcl_W-M-level-inv* *S*

shows *cdcl_W-M-level-inv* *S'*

using *assms* **unfolding** *full1-def*

proof –

have *cdcl_W-cp⁺⁺* *S S'* **and** *cdcl_W-M-level-inv* *S* **using** *assms* **unfolding** *full1-def* **by** *auto*

then show ?*thesis* **by** (*induct* rule: *trancpl.induct*) (*blast* intro: *cdcl_W-cp-consistent-inv*)+

qed

lemma *rtrancpl-cdcl_W-cp-consistent-inv*:

assumes *rtrancp cdcl_W-cp S S'*
and *cdcl_W-M-level-inv S*
shows *cdcl_W-M-level-inv S'*
using *assms unfolding full1-def*
by (*induction rule: rtrancp-induct*) (*blast intro: cdcl_W-cp-consistent-inv*)+

lemma *cdcl_W-stgy-consistent-inv*:
assumes *cdcl_W-stgy S S'*
and *cdcl_W-M-level-inv S*
shows *cdcl_W-M-level-inv S'*
using *assms apply (induct rule: cdcl_W-stgy.induct)*
unfolding *full-unfold* **by** (*blast intro: cdcl_W-consistent-inv full1-cdcl_W-cp-consistent-inv cdcl_W.other*)+

lemma *rtrancp-cdcl_W-stgy-consistent-inv*:
assumes *cdcl_W-stgy** S S'*
and *cdcl_W-M-level-inv S*
shows *cdcl_W-M-level-inv S'*
using *assms by induction (auto dest!: cdcl_W-stgy-consistent-inv)*

lemma *cdcl_W-cp-no-more-init-clss*:
assumes *cdcl_W-cp S S'*
shows *init-clss S = init-clss S'*
using *assms by (induct rule: cdcl_W-cp.induct) auto*

lemma *trancp-cdcl_W-cp-no-more-init-clss*:
assumes *cdcl_W-cp⁺⁺ S S'*
shows *init-clss S = init-clss S'*
using *assms by (induct rule: trancp.induct) (auto dest: cdcl_W-cp-no-more-init-clss)*

lemma *cdcl_W-stgy-no-more-init-clss*:
assumes *cdcl_W-stgy S S' and cdcl_W-M-level-inv S*
shows *init-clss S = init-clss S'*
using *assms*
apply (*induct rule: cdcl_W-stgy.induct*)
unfolding *full1-def full-def* **apply** (*blast dest: trancp-cdcl_W-cp-no-more-init-clss trancp-cdcl_W-o-no-more-init-clss*)
by (*metis cdcl_W-o-no-more-init-clss rtrancp-unfold trancp-cdcl_W-cp-no-more-init-clss*)

lemma *rtrancp-cdcl_W-stgy-no-more-init-clss*:
assumes *cdcl_W-stgy** S S' and cdcl_W-M-level-inv S*
shows *init-clss S = init-clss S'*
using *assms*
apply (*induct rule: rtrancp-induct, simp*)
using *cdcl_W-stgy-no-more-init-clss* **by** (*simp add: rtrancp-cdcl_W-stgy-consistent-inv*)

lemma *cdcl_W-cp-dropWhile-trail'*:
assumes *cdcl_W-cp S S'*
obtains *M where trail S' = M @ trail S and (∀ l ∈ set M. ¬is-marked l)*
using *assms by induction fastforce+*

lemma *rtrancp-cdcl_W-cp-dropWhile-trail'*:
assumes *cdcl_W-cp** S S'*
obtains *M :: ('v, nat, 'v clause) marked-lit list where trail S' = M @ trail S and ∀ l ∈ set M. ¬is-marked l*

using *assms* **by** *induction* (*fastforce* *dest!*: *cdcl_W-cp-dropWhile-trail'*)**+**

lemma *cdcl_W-cp-dropWhile-trail*:

assumes *cdcl_W-cp* *S S'*

shows $\exists M. \text{trail } S' = M @ \text{trail } S \wedge (\forall l \in \text{set } M. \neg \text{is-marked } l)$

using *assms* **by** *induction* *fastforce***+**

lemma *rtrancp-cdcl_W-cp-dropWhile-trail*:

assumes *cdcl_W-cp*** *S S'*

shows $\exists M. \text{trail } S' = M @ \text{trail } S \wedge (\forall l \in \text{set } M. \neg \text{is-marked } l)$

using *assms* **by** *induction* (*fastforce* *dest*: *cdcl_W-cp-dropWhile-trail*)**+**

This theorem can be seen as a termination theorem for *cdcl_W-cp*.

lemma *length-model-le-vars*:

assumes

no-strange-atm *S* **and**

no-d: *no-dup* (*trail* *S*) **and**

finite (*atms-of-msu* (*init-clss* *S*))

shows $\text{length} (\text{trail } S) \leq \text{card} (\text{atms-of-msu} (\text{init-clss } S))$

proof –

obtain *M N U k D* **where** *S*: *state* *S* = (*M*, *N*, *U*, *k*, *D*) **by** (*cases* *state* *S*, *auto*)

have *finite* (*atm-of* ‘*lits-of* (*trail* *S*)’)

using *assms*(1,3) **unfolding** *S* **by** (*auto* *simp* *add*: *finite-subset*)

have $\text{length} (\text{trail } S) = \text{card} (\text{atm-of} \text{ ‘lits-of } (\text{trail } S))$

using *no-dup-length-eq-card-atm-of-lits-of* *no-d* **by** *blast*

then show *?thesis* **using** *assms*(1) **unfolding** *no-strange-atm-def*

by (*auto* *simp* *add*: *assms*(3) *card-mono*)

qed

lemma *cdcl_W-cp-decreasing-measure*:

assumes

cdcl_W: *cdcl_W-cp* *S T* **and**

M-lev: *cdcl_W-M-level-inv* *S* **and**

alien: *no-strange-atm* *S*

shows $(\lambda S. \text{card} (\text{atms-of-msu} (\text{init-clss } S)) - \text{length} (\text{trail } S))$

$+ (\text{if } \text{conflicting } S = C\text{-True} \text{ then } 1 \text{ else } 0)) S$

$> (\lambda S. \text{card} (\text{atms-of-msu} (\text{init-clss } S)) - \text{length} (\text{trail } S))$

$+ (\text{if } \text{conflicting } S = C\text{-True} \text{ then } 1 \text{ else } 0)) T$

using *assms*

proof –

have $\text{length} (\text{trail } T) \leq \text{card} (\text{atms-of-msu} (\text{init-clss } T))$

apply (*rule* *length-model-le-vars*)

using *cdcl_W-no-strange-atm-inv* *alien* *M-lev* **apply** (*meson* *cdcl_W* *cdcl_W.simps* *cdcl_W-cp.cases*)

using *M-lev* *cdcl_W* *cdcl_W-cp-consistent-inv* *cdcl_W-M-level-inv-def* **apply** *blast*

using *cdcl_W* **by** (*auto* *simp*: *cdcl_W-cp.simps*)

with *assms*

show *?thesis* **by** *induction* (*auto* *split*: *split-if-asm*)**+**

qed

lemma *cdcl_W-cp-wf*: *wf* $\{(b,a). (\text{cdcl_W-M-level-inv } a \wedge \text{no-strange-atm } a)$

$\wedge \text{cdcl_W-cp } a \text{ } b)\}$

apply (*rule* *wf-wf-if-measure'*[*of* *less-than* - -

$(\lambda S. \text{card} (\text{atms-of-msu} (\text{init-clss } S)) - \text{length} (\text{trail } S))$

$+ (\text{if } \text{conflicting } S = C\text{-True} \text{ then } 1 \text{ else } 0))])$

apply *simp*

```

using cdclW-cp-decreasing-measure unfolding less-than-iff by blast

lemma rtrancpl-cdclW-all-struct-inv-cdclW-cp-iff-rtrancpl-cdclW-cp:
  assumes
    lev: cdclW-M-level-inv S and
    alien: no-strange-atm S
  shows (λa b. (cdclW-M-level-inv a ∧ no-strange-atm a) ∧ cdclW-cp a b)** S T
    ⟷ cdclW-cp** S T
  (is ?I S T ⟷ ?C S T)
proof
  assume
    ?I S T
  then show ?C S T by induction auto
next
  assume
    ?C S T
  then show ?I S T
  proof induction
    case base
    then show ?case by simp
  next
    case (step T U) note st = this(1) and cp = this(2) and IH = this(3)
    have cdclW** S T
      by (metis rtrancpl-unfold cdclW-cp-conflicting-not-empty cp st
        rtrancpl-propagate-is-rtrancpl-cdclW trancpl-cdclW-cp-propagate-with-conflict-or-not)
    then have
      cdclW-M-level-inv T and
      no-strange-atm T
      using ⟨cdclW** S T⟩ apply (simp add: assms(1) rtrancpl-cdclW-consistent-inv)
      using ⟨cdclW** S T⟩ alien rtrancpl-cdclW-no-strange-atm-inv lev by blast
    then have (λa b. (cdclW-M-level-inv a ∧ no-strange-atm a)
      ∧ cdclW-cp a b)** T U
      using cp by auto
    then show ?case using IH by auto
  qed
qed

lemma cdclW-cp-normalized-element:
  assumes
    lev: cdclW-M-level-inv S and
    no-strange-atm S
  obtains T where full cdclW-cp S T
proof -
  let ?inv = λa. (cdclW-M-level-inv a ∧ no-strange-atm a)
  obtain T where T: full (λa b. ?inv a ∧ cdclW-cp a b) S T
  using cdclW-cp-wf wf-exists-normal-form[of λa b. ?inv a ∧ cdclW-cp a b]
  unfolding full-def by blast
  then have cdclW-cp** S T
    using rtrancpl-cdclW-all-struct-inv-cdclW-cp-iff-rtrancpl-cdclW-cp assms unfolding full-def
    by blast
  moreover
    then have cdclW** S T
      using rtrancpl-cdclW-cp-rtrancpl-cdclW by blast
    then have
      cdclW-M-level-inv T and

```

no-strange-atm T
using $\langle \text{cdcl}_W^{**} S T \rangle$ **apply** (*simp add: assms(1) rtranclp-cdcl_W-consistent-inv*)
using $\langle \text{cdcl}_W^{**} S T \rangle$ *assms(2) rtranclp-cdcl_W-no-strange-atm-inv lev* **by** *blast*
then have *no-step cdcl_W-cp T*
using *T unfolding full-def* **by** *auto*
ultimately show *thesis* **using** *that unfolding full-def* **by** *blast*
qed

lemma *in-atms-of-implies-atm-of-on-atms-of-ms:*

$C + \{\#L\# \} \in \# A \implies x \in \text{atms-of } C \implies x \in \text{atms-of-msu } A$
by (*metis add.commute atm-iff-pos-or-neg-lit atms-of-atms-of-ms-mono contra-subsetD*
mem-set-mset-iff multi-member-skip)

lemma *propagate-no-strange-atm:*

assumes
propagate S S' and
no-strange-atm S
shows *no-strange-atm S'*
using *assms* **by** *induction*
(auto simp add: no-strange-atm-def clauses-def in-plus-implies-atm-of-on-atms-of-ms
in-atms-of-implies-atm-of-on-atms-of-ms)

lemma *always-exists-full-cdcl_W-cp-step:*

assumes *no-strange-atm S*
shows $\exists S''. \text{full cdcl}_W\text{-cp } S S''$
using *assms*

proof (*induct card (atms-of-msu (init-clss S) - atm-of 'lits-of (trail S)) arbitrary: S*)

case 0 **note** *card = this(1) and alien = this(2)*

then have *atm: atms-of-msu (init-clss S) = atm-of 'lits-of (trail S)*

unfolding *no-strange-atm-def* **by** *auto*

{ assume *a: $\exists S'. \text{conflict } S S'$*

then obtain *S' where S': conflict S S' by metis*

then have $\forall S''. \neg \text{cdcl}_W\text{-cp } S' S''$ **by** *auto*

then have *?case using a S' cdcl_W-cp.conflict' unfolding full-def* **by** *blast*

}

moreover {

assume *a: $\exists S'. \text{propagate } S S'$*

then obtain *S' where propagate S S' by blast*

then obtain *M N U k C L where S: state S = (M, N, U, k, C-True)*

and *S': state S' = (Propagated L ((C + {#L#})) # M, N, U, k, C-True)*

and $C + \{\#L\# \} \in \# \text{clauses } S$

and $M \models_{\text{as}} C \text{Not } C$

and *undefined-lit M L*

using *propagate* **by** *auto*

have *atms-of-msu U \subseteq atms-of-msu N* **using** *alien S unfolding no-strange-atm-def* **by** *auto*

then have *atm-of L \in atms-of-msu (init-clss S)*

using $\langle C + \{\#L\# \} \in \# \text{clauses } S \rangle$ *S* **unfolding** *atms-of-ms-def clauses-def* **by** *force+*

then have *False* **using** $\langle \text{undefined-lit } M L \rangle$ *S* **unfolding** *atm unfolding lits-of-def*

by (*auto simp add: defined-lit-map*)

}

ultimately show *?case* **by** (*metis cdcl_W-cp.cases full-def rtranclp.rtrancl-refl*)

next

case (*Suc n*) **note** *IH = this(1) and card = this(2) and alien = this(3)*

{ assume *a: $\exists S'. \text{conflict } S S'$*

then obtain *S' where S': conflict S S' by metis*


```

then have  $\forall S''. \neg \text{cdcl}_W\text{-cp } S' S''$  by auto
then have ?case unfolding full-def Ex-def using  $S' \text{ cdcl}_W\text{-cp.conflict'}$  by blast
}
moreover {
  assume a:  $\exists S'. \text{propagate } S S'$ 
  then obtain  $S'$  where propagate:  $\text{propagate } S S'$  by blast
  then obtain  $M N U k C L$  where
     $S$ : state  $S = (M, N, U, k, C\text{-True})$  and
     $S'$ : state  $S' = (\text{Propagated } L ( (C + \{\#L\# \}))) \# M, N, U, k, C\text{-True}$  and
     $C + \{\#L\# \} \in \# \text{ clauses } S$  and
     $M \models_{as} C \text{Not } C$  and
    undefined-lit  $M L$ 
  by fastforce
  then have  $\text{atm-of } L \notin \text{atm-of ' lits-of } M$ 
  unfolding lits-of-def by (auto simp add: defined-lit-map)
  moreover
    have no-strange-atm  $S'$  using alien propagate propagate-no-strange-atm by blast
    then have  $\text{atm-of } L \in \text{atms-of-msu } N$  using  $S'$  unfolding no-strange-atm-def by auto
    then have  $\bigwedge A. \{\text{atm-of } L\} \subseteq \text{atms-of-msu } N - A \vee \text{atm-of } L \in A$  by force
  moreover have  $\text{Suc } n - \text{card } \{\text{atm-of } L\} = n$  by simp
  moreover have  $\text{card } (\text{atms-of-msu } N - \text{atm-of ' lits-of } M) = \text{Suc } n$ 
  using card  $S S'$  by simp
  ultimately
    have  $\text{card } (\text{atms-of-msu } N - \text{atm-of ' insert } L (\text{lits-of } M)) = n$ 
    by (metis (no-types) Diff-insert card-Diff-subset finite.emptyI finite.insertI image-insert)
    then have  $n = \text{card } (\text{atms-of-msu } (\text{init-clss } S') - \text{atm-of ' lits-of } (\text{trail } S'))$ 
    using card  $S S'$  by simp
  then have a1:  $\text{Ex } (\text{full cdcl}_W\text{-cp } S')$  using IH  $\langle \text{no-strange-atm } S' \rangle$  by blast
  have ?case
    proof -
      obtain  $S'' :: 'st$  where
        ff1:  $\text{cdcl}_W\text{-cp}^{**} S' S'' \wedge \text{no-step cdcl}_W\text{-cp } S''$ 
        using a1 unfolding full-def by blast
      have  $\text{cdcl}_W\text{-cp}^{**} S S''$ 
        using ff1  $\text{cdcl}_W\text{-cp.intros}(2)[OF \text{ propagate}]$ 
        by (metis (no-types) converse-rtranclp-into-rtranclp)
      then have  $\exists S''. \text{cdcl}_W\text{-cp}^{**} S S'' \wedge (\forall S'''. \neg \text{cdcl}_W\text{-cp } S'' S''')$ 
        using ff1 by blast
      then show ?thesis unfolding full-def
        by meson
    qed
  }
ultimately show ?case unfolding full-def by (metis  $\text{cdcl}_W\text{-cp.cases rtranclp.rtrancl-refl}$ )
qed

```

17.6.3 Literal of highest level in conflicting clauses

One important property of the cdcl_W with strategy is that, whenever a conflict takes place, there is at least a literal of level k involved (except if we have derived the false clause). The reason is that we apply conflicts before a decision is taken.

abbreviation $\text{no-clause-is-false} :: 'st \Rightarrow \text{bool}$ **where**

$\text{no-clause-is-false} \equiv$

$\lambda S. (\text{conflicting } S = C\text{-True} \longrightarrow (\forall D \in \# \text{ clauses } S. \neg \text{trail } S \models_{as} C \text{Not } D))$

abbreviation $\text{conflict-is-false-with-level} :: 'st \Rightarrow \text{bool}$ **where**

conflict-is-false-with-level $S' \equiv \forall D. \text{conflicting } S' = C\text{-Clause } D \longrightarrow D \neq \{\#\}$
 $\longrightarrow (\exists L \in \# D. \text{get-level } L (\text{trail } S') = \text{backtrack-lvl } S')$

lemma *not-conflict-not-any-negated-init-clss*:

assumes $\forall S'. \neg \text{conflict } S S'$
shows *no-clause-is-false* S
using *assms state-eq-ref* **by** *blast*

lemma *full-cdcl_W-cp-not-any-negated-init-clss*:

assumes *full cdcl_W-cp* $S S'$
shows *no-clause-is-false* S'
using *assms not-conflict-not-any-negated-init-clss* **unfolding** *full-def* **by** *blast*

lemma *full1-cdcl_W-cp-not-any-negated-init-clss*:

assumes *full1 cdcl_W-cp* $S S'$
shows *no-clause-is-false* S'
using *assms not-conflict-not-any-negated-init-clss* **unfolding** *full1-def* **by** *blast*

lemma *cdcl_W-stgy-not-non-negated-init-clss*:

assumes *cdcl_W-stgy* $S S'$
shows *no-clause-is-false* S'
using *assms apply* (*induct rule: cdcl_W-stgy.induct*)
using *full1-cdcl_W-cp-not-any-negated-init-clss* *full-cdcl_W-cp-not-any-negated-init-clss* **by** *metis+*

lemma *rtranclp-cdcl_W-stgy-not-non-negated-init-clss*:

assumes *cdcl_W-stgy*** $S S'$ **and** *no-clause-is-false* S
shows *no-clause-is-false* S'
using *assms* **by** (*induct rule: rtranclp-induct*) (*auto simp: cdcl_W-stgy-not-non-negated-init-clss*)

lemma *cdcl_W-stgy-conflict-ex-lit-of-max-level*:

assumes *cdcl_W-cp* $S S'$
and *no-clause-is-false* S
and *cdcl_W-M-level-inv* S
shows *conflict-is-false-with-level* S'
using *assms*

proof (*induct rule: cdcl_W-cp.induct*)

case *conflict'*
then show *?case* **by** *auto*

next

case *propagate'*
then show *?case* **by** *auto*

qed

lemma *no-chained-conflict*:

assumes *conflict* $S S'$
and *conflict* $S' S''$
shows *False*
using *assms* **by** *fastforce*

lemma *rtranclp-cdcl_W-cp-propa-or-propa-confl*:

assumes *cdcl_W-cp*** $S U$
shows *propagate*** $S U \vee (\exists T. \text{propagate** } S T \wedge \text{conflict } T U)$
using *assms*

proof *induction*

case *base*

```

then show ?case by auto
next
case (step U V) note SU = this(1) and UV = this(2) and IH = this(3)
consider (confl) T where propagate** S T and conflict T U
  | (propa) propagate** S U using IH by auto
then show ?case
proof cases
  case confl
  then have False using UV by auto
  then show ?thesis by fast
next
case propa
also have conflict U V  $\vee$  propagate U V using UV by (auto simp add: cdclW-cp.simps)
ultimately show ?thesis by force
qed
qed

lemma rtranclp-cdclW-co-conflict-ex-lit-of-max-level:
  assumes full: full cdclW-cp S U
  and cls-f: no-clause-is-false S
  and conflict-is-false-with-level S
  and lev: cdclW-M-level-inv S
  shows conflict-is-false-with-level U
proof (intro allI impI)
  fix D
  assume confl: conflicting U = C-Clause D and
    D: D  $\neq$  {#}
  consider (CT) conflicting S = C-True | (SD) D' where conflicting S = C-Clause D'
  by (cases conflicting S) auto
  then show  $\exists L \in \#D. \text{get-level } L (\text{trail } U) = \text{backtrack-lvl } U$ 
  proof cases
    case SD
    then have S = U
      by (metis (no-types) assms(1) cdclW-cp-conflicting-not-empty full-def rtranclpD tranclpD)
    then show ?thesis using assms(3) confl D by blast
  next
  case CT
  have init-clss U = init-clss S and learned-clss U = learned-clss S
    using assms(1) unfolding full-def
    apply (metis (no-types) rtranclpD tranclp-cdclW-cp-no-more-init-clss)
    by (metis (mono-tags, lifting) assms(1) full-def rtranclp-cdclW-cp-learned-clause-inv)
  obtain T where propagate** S T and TU: conflict T U
  proof -
    have f5: U  $\neq$  S
      using confl CT by force
    then have cdclW-cp++ S U
      by (metis full full-def rtranclpD)
    have  $\bigwedge p \text{ pa. } \neg \text{propagate } p \text{ pa} \vee \text{conflicting } \text{pa} =$ 
      (C-True::'v literal multiset conflicting-clause)
      by auto
    then show ?thesis
      using f5 that tranclp-cdclW-cp-propagate-with-conflict-or-not[OF  $\langle \text{cdcl}_W\text{-cp}^{++} S U \rangle$ ]
      full confl CT unfolding full-def by auto
  qed
  have init-clss T = init-clss S and learned-clss T = learned-clss S

```

```

    using TU  $\langle \text{init-clss } U = \text{init-clss } S \rangle \langle \text{learned-clss } U = \text{learned-clss } S \rangle$  by auto
  then have  $D \in \# \text{ clauses } S$ 
    using TU confl by (fastforce simp: clauses-def)
  then have  $\neg \text{trail } S \models_{\text{as}} \text{CNot } D$ 
    using cls-f CT by simp
  moreover
    obtain  $M$  where  $\text{tr-}U: \text{trail } U = M @ \text{trail } S$  and  $\text{nm}: \forall m \in \text{set } M. \neg \text{is-marked } m$ 
      by (metis (mono-tags, lifting) assms(1) full-def rtrancplp-cdclW-cp-dropWhile-trail)
    have  $\text{trail } U \models_{\text{as}} \text{CNot } D$ 
      using TU confl by auto
  ultimately obtain  $L$  where  $L \in \# D$  and  $\neg L \in \text{lits-of } M$ 
    unfolding tr-U CNot-def true-annot-def Ball-def true-annot-def true-clss-def by auto

  moreover have  $\text{inv-}U: \text{cdcl}_W\text{-}M\text{-level-inv } U$ 
    by (metis cdclW-stgy.conflict' cdclW-stgy-consistent-inv full full-unfold lev)
  moreover
    have  $\text{backtrack-lvl } U = \text{backtrack-lvl } S$ 
      using full unfolding full-def by (auto dest: rtrancplp-cdclW-cp-backtrack-lvl)

  moreover
    have no-dup (trail U)
      using inv-U unfolding cdclW-M-level-inv-def by auto
    { fix  $x :: ('v, \text{nat}, 'v \text{ literal multiset}) \text{ marked-lit}$  and
       $xb :: ('v, \text{nat}, 'v \text{ literal multiset}) \text{ marked-lit}$ 
      assume  $a1: \text{atm-of } L = \text{atm-of } (\text{lit-of } xb)$ 
      moreover assume  $a2: \neg L = \text{lit-of } x$ 
      moreover assume  $a3: (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ ' set } M$ 
         $\cap (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ ' set } (\text{trail } S) = \{\}$ 
      moreover assume  $a4: x \in \text{set } M$ 
      moreover assume  $a5: xb \in \text{set } (\text{trail } S)$ 
      moreover have  $\text{atm-of } (\neg L) = \text{atm-of } L$ 
        by auto
      ultimately have False
        by auto
    }
  then have  $LS: \text{atm-of } L \notin \text{atm-of ' lits-of } (\text{trail } S)$ 
    using  $\langle \neg L \in \text{lits-of } M \rangle \langle \text{no-dup } (\text{trail } U) \rangle$  unfolding tr-U lits-of-def by auto
  ultimately have  $\text{get-level } L (\text{trail } U) = \text{backtrack-lvl } U$ 
  proof (cases get-all-levels-of-marked (trail S)  $\neq []$ , goal-cases)
    case 2 note  $LD = \text{this}(1)$  and  $LM = \text{this}(2)$  and  $\text{inv-}U = \text{this}(3)$  and  $US = \text{this}(4)$  and
       $LS = \text{this}(5)$  and  $ne = \text{this}(6)$ 
    have  $\text{backtrack-lvl } S = 0$ 
      using lev ne unfolding cdclW-M-level-inv-def by auto
    moreover have  $\text{get-rev-level } L 0 (\text{rev } M) = 0$ 
      using nm by auto
    ultimately show ?thesis using  $LS \ ne \ US$  unfolding tr-U
      by (simp add: get-all-levels-of-marked-nil-iff-not-is-marked lits-of-def)
  next
    case 1 note  $LD = \text{this}(1)$  and  $LM = \text{this}(2)$  and  $\text{inv-}U = \text{this}(3)$  and  $US = \text{this}(4)$  and
       $LS = \text{this}(5)$  and  $ne = \text{this}(6)$ 

    have  $hd (\text{get-all-levels-of-marked } (\text{trail } S)) = \text{backtrack-lvl } S$ 
      using ne lev unfolding cdclW-M-level-inv-def
      by (cases get-all-levels-of-marked (trail S)) auto
    moreover have  $\text{atm-of } L \in \text{atm-of ' lits-of } M$ 

```

```

    using  $\langle -L \in \text{ lits-of } M \rangle$  by (simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
      lits-of-def)
  ultimately show ?thesis
    using nm ne unfolding tr-U
    using get-level-skip-beginning-hd-get-all-levels-of-marked[OF LS, of M]
      get-level-skip-in-all-not-marked[of rev M L backtrack-lvl S]
    unfolding lits-of-def US
    by auto
  qed
then show  $\exists L \in \#D. \text{ get-level } L (\text{ trail } U) = \text{ backtrack-lvl } U$ 
  using  $\langle L \in \#D \rangle$  by blast
qed
qed

```

17.6.4 Literal of highest level in marked literals

definition *mark-is-false-with-level* :: 'st \Rightarrow bool **where**

mark-is-false-with-level $S' \equiv$

$\forall D \ M1 \ M2 \ L. \ M1 \ @ \ \text{Propagated } L \ D \ \# \ M2 = \text{ trail } S' \longrightarrow D - \{\#L\} \neq \{\#\}$
 $\longrightarrow (\exists L. L \in \#D \wedge \text{ get-level } L (\text{ trail } S') = \text{ get-maximum-possible-level } M1)$

definition *no-more-propagation-to-do*:: 'st \Rightarrow bool **where**

no-more-propagation-to-do $S \equiv$

$\forall D \ M \ M' \ L. D + \{\#L\} \in \# \text{ clauses } S \longrightarrow \text{ trail } S = M' \ @ \ M \longrightarrow M \models_{as} CNot \ D$
 $\longrightarrow \text{ undefined-lit } M \ L \longrightarrow \text{ get-maximum-possible-level } M < \text{ backtrack-lvl } S$
 $\longrightarrow (\exists L. L \in \#D \wedge \text{ get-level } L (\text{ trail } S) = \text{ get-maximum-possible-level } M)$

lemma *propagate-no-more-propagation-to-do*:

assumes *propagate*: *propagate* $S \ S'$
and H : *no-more-propagation-to-do* S
and M : *cdcl_W-M-level-inv* S
shows *no-more-propagation-to-do* S'
using *assms*

proof –

obtain $M \ N \ U \ k \ C \ L$ **where**

S : *state* $S = (M, N, U, k, C-True)$ **and**

S' : *state* $S' = (\text{Propagated } L \ (C + \{\#L\})) \ \# \ M, N, U, k, C-True)$ **and**

$C + \{\#L\} \in \# \text{ clauses } S$ **and**

$M \models_{as} CNot \ C$ **and**

undefined-lit $M \ L$

using *propagate* **by** *auto*

let $?M' = \text{Propagated } L \ (C + \{\#L\}) \ \# \ M$

show ?thesis **unfolding** *no-more-propagation-to-do-def*

proof (intro allI impI)

fix $D \ M1 \ M2 \ L'$

assume $D-L$: $D + \{\#L'\} \in \# \text{ clauses } S'$

and $\text{ trail } S' = M2 \ @ \ M1$

and *get-max*: *get-maximum-possible-level* $M1 < \text{ backtrack-lvl } S'$

and $M1 \models_{as} CNot \ D$

and *undef*: *undefined-lit* $M1 \ L'$

have $tl \ M2 \ @ \ M1 = \text{ trail } S \vee (M2 = [] \wedge M1 = \text{Propagated } L \ (C + \{\#L\})) \ \# \ M$

using $\langle \text{ trail } S' = M2 \ @ \ M1 \rangle \ S' \ S$ **by** (cases $M2$) *auto*

moreover {

assume $tl \ M2 \ @ \ M1 = \text{ trail } S$

moreover **have** $D + \{\#L'\} \in \# \text{ clauses } S$ **using** $D-L \ S \ S'$ **unfolding** *clauses-def* **by** *auto*

moreover **have** *get-maximum-possible-level* $M1 < \text{ backtrack-lvl } S$

```

    using get-max S S' by auto
  ultimately obtain L' where L' ∈# D and
    get-level L' (trail S) = get-maximum-possible-level M1
    using H ⟨M1 ⊨as CNot D⟩ undef unfolding no-more-propagation-to-do-def by metis
  moreover
    { have cdclW-M-level-inv S'
      using cdclW-consistent-inv[OF - M] cdclW.propagate[OF propagate] by blast
      then have no-dup ?M' using S' unfolding cdclW-M-level-inv-def by auto
      moreover
        have atm-of L' ∈ atm-of ' (lits-of M1)
          using ⟨L' ∈# D⟩ ⟨M1 ⊨as CNot D⟩ by (metis atm-of-uminus image-eqI
            in-CNot-implies-uminus(2))
        then have atm-of L' ∈ atm-of ' (lits-of M)
          using ⟨tl M2 @ M1 = trail S⟩ S by auto
        ultimately have atm-of L ≠ atm-of L' unfolding lits-of-def by auto
      }
    ultimately have ∃ L' ∈# D. get-level L' (trail S') = get-maximum-possible-level M1
      using S S' by auto
  }
  moreover {
    assume M2 = [] and M1: M1 = Propagated L ( (C + {#L#})) # M
    have cdclW-M-level-inv S'
      using cdclW-consistent-inv[OF - M] cdclW.propagate[OF propagate] by blast
    then have get-all-levels-of-marked (trail S') = rev ([Suc 0..W-M-level-inv-def by auto
    then have get-maximum-possible-level M1 = backtrack-lvl S'
      using get-maximum-possible-level-max-get-all-levels-of-marked[of M1] S' M1
      by (auto intro: Max-eqI)
    then have False using get-max by auto
  }
  ultimately show ∃ L. L ∈# D ∧ get-level L (trail S') = get-maximum-possible-level M1 by fast
qed
qed

```

lemma *conflict-no-more-propagation-to-do:*

```

  assumes conflict: conflict S S'
  and H: no-more-propagation-to-do S
  and M: cdclW-M-level-inv S
  shows no-more-propagation-to-do S'
  using assms unfolding no-more-propagation-to-do-def conflict.simps by force

```

lemma *cdcl_W-cp-no-more-propagation-to-do:*

```

  assumes conflict: cdclW-cp S S'
  and H: no-more-propagation-to-do S
  and M: cdclW-M-level-inv S
  shows no-more-propagation-to-do S'
  using assms
  proof (induct rule: cdclW-cp.induct)
  case (conflict' S S')
  then show ?case using conflict-no-more-propagation-to-do[of S S'] by blast
next
  case (propagate' S S') note S = this
  show 1: no-more-propagation-to-do S'
    using propagate-no-more-propagation-to-do[of S S'] S by blast
qed

```

lemma *cdcl_W-then-exists-cdcl_W-stgy-step*:

assumes

o: *cdcl_W-o* *S S'* **and**
alien: *no-strange-atm* *S* **and**
lev: *cdcl_W-M-level-inv* *S*

shows $\exists S'. \text{cdcl}_W\text{-stgy } S S'$

proof –

obtain *S''* **where** *full cdcl_W-cp* *S' S''*

using *always-exists-full-cdcl_W-cp-step* *alien cdcl_W-no-strange-atm-inv cdcl_W-o-no-more-init-clss*
o other lev **by** (*meson cdcl_W-consistent-inv*)

then show *?thesis*

using *assms* **by** (*metis always-exists-full-cdcl_W-cp-step cdcl_W-stgy.conflict' full-unfold other'*)

qed

lemma *backtrack-no-decomp*:

assumes *S*: *state* *S* = (*M*, *N*, *U*, *k*, *C-Clause* (*D* + {*#L#*}))

and *L*: *get-level* *L M* = *k*

and *D*: *get-maximum-level* *D M* < *k*

and *M-L*: *cdcl_W-M-level-inv* *S*

shows $\exists S'. \text{cdcl}_W\text{-o } S S'$

proof –

have *L-D*: *get-level* *L M* = *get-maximum-level* (*D* + {*#L#*}) *M*

using *L D* **by** (*simp add: get-maximum-level-plus*)

let *?i* = *get-maximum-level* *D M*

obtain *K M1 M2* **where** *K*: (*Marked* *K* (*?i* + 1) *# M1, M2*) \in *set (get-all-marked-decomposition*
M)

using *backtrack-ex-decomp*[*OF M-L, of ?i*] *D S* **by** *auto*

show *?thesis* **using** *backtrack-rule*[*OF S K L L-D*] **by** (*meson bj cdcl_W-bj.simps state-eq-ref*)

qed

lemma *cdcl_W-stgy-final-state-conclusive*:

assumes *termi*: $\forall S'. \neg \text{cdcl}_W\text{-stgy } S S'$

and *decomp*: *all-decomposition-implies-m* (*init-clss* *S*) (*get-all-marked-decomposition* (*trail* *S*))

and *learned*: *cdcl_W-learned-clause* *S*

and *level-inv*: *cdcl_W-M-level-inv* *S*

and *alien*: *no-strange-atm* *S*

and *no-dup*: *distinct-cdcl_W-state* *S*

and *confl*: *cdcl_W-conflicting* *S*

and *confl-k*: *conflict-is-false-with-level* *S*

shows (*conflicting* *S* = *C-Clause* {*#*} \wedge *unsatisfiable* (*set-mset* (*init-clss* *S*)))

\vee (*conflicting* *S* = *C-True* \wedge *trail* *S* $\models_{\text{as set-mset}}$ (*init-clss* *S*))

proof –

let *?M* = *trail* *S*

let *?N* = *init-clss* *S*

let *?k* = *backtrack-lvl* *S*

let *?U* = *learned-clss* *S*

have *conflicting* *S* = *C-Clause* {*#*}

\vee *conflicting* *S* = *C-True*

\vee ($\exists D L. \text{conflicting } S = \text{C-Clause } (D + \{\#L\})$)

apply (*case-tac* *conflicting* *S*, *auto*)

by (*case-tac* *x2*, *auto*)

moreover {

assume *conflicting* *S* = *C-Clause* {*#*}

then have *unsatisfiable* (*set-mset* (*init-clss* *S*))

```

using assms( $\beta$ ) unfolding cdclW-learned-clause-def true-clss-cl-def
by (metis (no-types, lifting) Un-insert-right atms-of-empty satisfiable-def
sup-bot.right-neutral total-over-m-insert total-over-set-empty true-clss-empty)
}
moreover {
  assume conflicting S = C-True
  { assume  $\neg ?M \models_{asm} ?N$ 
    have atm-of ' (lits-of ?M) = atms-of-msu ?N (is ?A = ?B)
    proof
      show ?A  $\subseteq$  ?B using alien unfolding no-strange-atm-def by auto
      show ?B  $\subseteq$  ?A
      proof (rule ccontr)
        assume  $\neg ?B \subseteq ?A$ 
        then obtain l where  $l \in ?B$  and  $l \notin ?A$  by auto
        then have undefined-lit ?M (Pos l)
          using  $\langle l \notin ?A \rangle$  unfolding lits-of-def by (auto simp add: defined-lit-map)
        then have  $\exists S'. \text{cdcl}_W\text{-o } S S'$ 
          using cdclW-o.decide decide.intros  $\langle l \in ?B \rangle$  no-strange-atm-def
          by (metis  $\langle \text{conflicting } S = C\text{-True} \rangle$  literal.sel(1) state-eq-def)
        then show False
          using termi cdclW-then-exists-cdclW-stgy-step[OF - alien] level-inv by blast
      qed
    qed
    obtain D where  $\neg ?M \models_a D$  and  $D \in \# ?N$ 
      using  $\langle \neg ?M \models_{asm} ?N \rangle$  unfolding lits-of-def true-annots-def Ball-def by auto
    have atms-of D  $\subseteq$  atm-of ' (lits-of ?M)
      using  $\langle D \in \# ?N \rangle$  unfolding  $\langle \text{atm-of ' (lits-of ?M) = atms-of-msu ?N} \rangle$  atms-of-ms-def
      by (auto simp add: atms-of-def)
    then have a1: atm-of ' set-mset D  $\subseteq$  atm-of ' lits-of (trail S)
      by (auto simp add: atms-of-def lits-of-def)
    have total-over-m (lits-of ?M) {D}
      using  $\langle \text{atms-of } D \subseteq \text{atm-of ' (lits-of ?M)} \rangle$  atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
      by (fastforce simp: total-over-set-def)
    then have ?M  $\models_{as}$  CNot D
      using total-not-true-clss-true-clss-CNot  $\langle \neg \text{trail } S \models_a D \rangle$  true-annot-def
      true-annots-true-clss by fastforce
    then have False
    proof -
      obtain S' where
        f2: full cdclW-cp S S'
        by (meson alien always-exists-full-cdclW-cp-step level-inv)
      then have S' = S
        using cdclW-stgy.conflict'[of S] by (metis (no-types) full-unfold termi)
      then show ?thesis
        using f2  $\langle D \in \# \text{init-clss } S \rangle$   $\langle \text{conflicting } S = C\text{-True} \rangle$   $\langle \text{trail } S \models_{as} C\text{Not } D \rangle$ 
        clauses-def full-cdclW-cp-not-any-negated-init-clss by auto
    qed
  }
  then have ?M  $\models_{asm}$  ?N by blast
}
moreover {
  assume  $\exists D L. \text{conflicting } S = C\text{-Clause } (D + \{\#L\# \})$ 
  obtain D L where LD: conflicting S = C-Clause (D + {#L#}) and get-level L ?M = ?k
  proof -
    obtain mm :: 'v literal multiset and ll :: 'v literal where

```



```

  f2: conflicting S = C-Clause (mm + {#ll#})
  using ⟨∃ D L. conflicting S = C-Clause (D + {#L#})⟩ by force
  have ∀ m. (conflicting S ≠ C-Clause m ∨ m = {#})
    ∨ (∃ l. l ∈ # m ∧ get-level l (trail S) = backtrack-lvl S)
  using confl-k by blast
  then show ?thesis
    using f2 that by (metis (no-types) multi-member-split single-not-empty union-eq-empty)
  qed
let ?D = D + {#L#}
have ?D ≠ {#} by auto
have ?M ⊨as CNot ?D using confl LD unfolding cdclW-conflicting-def by auto
then have ?M ≠ [] unfolding true-annot-def Ball-def true-annot-def true-cls-def by force
{ have M: ?M = hd ?M # tl ?M using ⟨?M ≠ []⟩ list.collapse by fastforce
  assume marked: is-marked (hd ?M)
  then obtain k' where k': k' + 1 = ?k
    using level-inv M unfolding cdclW-M-level-inv-def
    by (cases hd (trail S); cases trail S) auto
  obtain L' l' where L': hd ?M = Marked L' l' using marked by (case-tac hd ?M) auto
  have get-all-levels-of-marked (hd (trail S) # tl (trail S))
    = rev [1..<1 + length (get-all-levels-of-marked ?M)]
    using level-inv ⟨get-level L ?M = ?k⟩ M unfolding cdclW-M-level-inv-def M[symmetric]
    by blast
  then have l'-tl: l' # get-all-levels-of-marked (tl ?M)
    = rev [1..<1 + length (get-all-levels-of-marked ?M)] unfolding L' by simp
  moreover have ... = length (get-all-levels-of-marked ?M)
    # rev [1..W-M-level-inv-def by auto
  have *: ∧list. no-dup list ⇒
    - L ∈ lits-of list ⇒ atm-of L ∈ atm-of ' lits-of list
    by (metis atm-of-uminus imageI)
  have L' = -L
  proof (rule ccontr)
    assume ¬ ?thesis
    moreover have -L ∈ lits-of ?M using confl LD unfolding cdclW-conflicting-def by auto
    ultimately have get-level L (hd (trail S) # tl (trail S)) = get-level L (tl ?M)
      using cdclW-M-level-inv-decomp(1)[OF level-inv] unfolding L' consistent-interp-def
      by (metis (no-types, lifting) L' M atm-of-eq-atm-of get-level-skip-beginning insert-iff
        lits-of-cons marked-lit.sel(1))

  moreover
    have length (get-all-levels-of-marked (trail S)) = ?k
      using level-inv unfolding cdclW-M-level-inv-def by auto
    then have Max (set (0 # get-all-levels-of-marked (tl (trail S)))) = ?k - 1
      unfolding g-r by (auto simp add: Max-n-upt)
    then have get-level L (tl ?M) < ?k
      using get-maximum-possible-level-ge-get-level[of L tl ?M]
      by (metis One-nat-def add.right-neutral add-Suc-right diff-add-inverse2
        get-maximum-possible-level-max-get-all-levels-of-marked k' le-imp-less-Suc
        list.simps(15))
    finally show False using ⟨get-level L ?M = ?k⟩ M by auto
}

```

```

qed
have L: hd ?M = Marked (-L) ?k using ⟨l' = ?k⟩ ⟨L' = -L⟩ L' by auto

have g-a-l: get-all-levels-of-marked ?M = rev [1..<1 + ?k]
  using level-inv ⟨get-level L ?M = ?k⟩ M unfolding cdclW-M-level-inv-def by auto
have g-k: get-maximum-level D (trail S) ≤ ?k
  using get-maximum-possible-level-ge-get-maximum-level[of D ?M]
    get-maximum-possible-level-max-get-all-levels-of-marked[of ?M]
  by (auto simp add: Max-n-upt g-a-l)
have get-maximum-level D (trail S) < ?k
  proof (rule ccontr)
    assume ¬ ?thesis
    then have get-maximum-level D (trail S) = ?k using M g-k unfolding L by auto
    then obtain L' where L' ∈# D and L-k: get-level L' ?M = ?k
      using get-maximum-level-exists-lit[of ?k D ?M] unfolding k[symmetric] by auto
    have L ≠ L' using no-dup ⟨L' ∈# D⟩
      unfolding distinct-cdclW-state-def LD by (metis add.commute add-eq-self-zero
        count-single count-union less-not-refl3 distinct-mset-def union-single-eq-member)
    have L' = -L
      proof (rule ccontr)
        assume ¬ ?thesis
        then have get-level L' ?M = get-level L' (tl ?M)
          using M ⟨L ≠ L'⟩ get-level-skip-beginning[of L' hd ?M tl ?M] unfolding L
          by (auto simp add: atm-of-eq-atm-of)
        moreover have ... < ?k
          using level-inv g-r get-rev-level-less-max-get-all-levels-of-marked[of L' 0
            rev (tl ?M)] L-k l'-tl calculation g-a-l
          by (auto simp add: Max-n-upt cdclW-M-level-inv-def)
        finally show False using L-k by simp
      qed
    qed
    then have taut: tautology (D + {#L#})
      using ⟨L' ∈# D⟩ by (metis add.commute mset-leD mset-le-add-left multi-member-this
        tautology-minus)
    have consistent-interp (lits-of ?M)
      using level-inv unfolding cdclW-M-level-inv-def by auto
    then have ¬?M ⊨as CNot ?D
      using taut by (metis (no-types) ⟨L' = -L⟩ ⟨L' ∈# D⟩ add.commute consistent-interp-def
        in-CNot-implies-uminus(2) mset-leD mset-le-add-left multi-member-this)
    moreover have ?M ⊨as CNot ?D
      using confl no-dup LD unfolding cdclW-conflicting-def by auto
    ultimately show False by blast
  qed
qed
then have False
  using backtrack-no-decomp[OF - ⟨get-level L (trail S) = backtrack-lvl S⟩ - level-inv]
  LD alien termi by (metis cdclW-then-exists-cdclW-stgy-step level-inv)
}
moreover {
  assume ¬is-marked (hd ?M)
  then obtain L' C where L'C: hd ?M = Propagated L' C by (case-tac hd ?M, auto)
  then have M: ?M = Propagated L' C # tl ?M using ⟨?M ≠ []⟩ list.collapse by fastforce
  then obtain C' where C': C = C' + {#L'#}
    using confl unfolding cdclW-conflicting-def by (metis append-Nil diff-single-eq-union)
  { assume -L' ∉# ?D
    then have False
      using bj[OF cdclW-bj.skip[OF skip-rule[OF - ⟨-L' ∉# ?D⟩ ⟨?D ≠ {#}⟩, of S C tl (trail S) -

```

```

]]]
termi M by (metis LD alien cdclW-then-exists-cdclW-stgy-step state-eq-def level-inv)
}
moreover {
  assume  $-L' \in \# \text{ ?D}$ 
  then obtain D' where D':  $\text{?D} = D' + \{\#-L'\# \}$  by (metis insert-DiffM2)
  have g-r: get-all-levels-of-marked (Propagated L' C # tl (trail S))
    = rev [Suc 0.. $\text{Suc} (\text{length} (\text{get-all-levels-of-marked} (\text{trail S})))$ ]
    using level-inv M unfolding cdclW-M-level-inv-def by auto
  have Max (insert 0 (set (get-all-levels-of-marked (Propagated L' C # tl (trail S))))) = ?k
    using level-inv M unfolding g-r cdclW-M-level-inv-def set-rev
    by (auto simp add:Max-n-upt)
  then have get-maximum-level D' (Propagated L' C # tl ?M)  $\leq$  ?k
    using get-maximum-possible-level-ge-get-maximum-level[of D' Propagated L' C # tl ?M]
    unfolding get-maximum-possible-level-max-get-all-levels-of-marked by auto
  then have get-maximum-level D' (Propagated L' C # tl ?M) = ?k
     $\vee$  get-maximum-level D' (Propagated L' C # tl ?M) < ?k
    using le-neq-implies-less by blast
  moreover {
    assume g-D'-k: get-maximum-level D' (Propagated L' C # tl ?M) = ?k
    have False
    proof -
      have f1: get-maximum-level D' (trail S) = backtrack-lvl S
        using M g-D'-k by auto
      have (trail S, init-clss S, learned-clss S, backtrack-lvl S, C-Clause (D + {#L#}))
        = state S
        by (metis (no-types) LD)
      then have cdclW-o S (update-conflicting (C-Clause (D' # $\cup$  C')) (tl-trail S))
        using f1 bj[OF cdclW-bj.resolve[OF resolve-rule[of S L' C' tl ?M ?N ?U ?k D]]]
        C' D' M by (metis state-eq-def)
      then show ?thesis
        by (meson alien cdclW-then-exists-cdclW-stgy-step termi level-inv)
    qed
  }
}
moreover {
  assume get-maximum-level D' (Propagated L' C # tl ?M) < ?k
  then have False
  proof -
    assume a1: get-maximum-level D' (Propagated L' C # tl (trail S)) < backtrack-lvl S
    obtain mm :: 'v literal multiset and ll :: 'v literal where
      f2: conflicting S = C-Clause (mm + {#ll#})
      get-level ll (trail S) = backtrack-lvl S
      using LD (get-level L (trail S) = backtrack-lvl S) by blast
    then have f3: get-maximum-level D' (trail S)  $\leq$  get-level ll (trail S)
      using M a1 by force
    have get-level ll (trail S)  $\neq$  get-maximum-level D' (trail S)
      using f2 M calculation(2) by presburger
    have f1: trail S = Propagated L' C # tl (trail S)
      conflicting S = C-Clause (D' + {#- L'#})
      using D' LD M by force+
    have f2: conflicting S = C-Clause (mm + {#ll#})
      get-level ll (trail S) = backtrack-lvl S
      using f2 by force+
    have ll = - L'
      by (metis (no-types) D' LD (get-level ll (trail S)  $\neq$  get-maximum-level D' (trail S))

```

```

      conflicting-clause.inject f2 f3 get-maximum-level-ge-get-level insert-noteq-member
      le-antisym)
    then show ?thesis
      using f2 f1 M backtrack-no-decomp[of S]
      by (metis (no-types) a1 alien cdclW-then-exists-cdclW-stgy-step level-inv termi)
  qed
}
ultimately have False by blast
}
ultimately have False by blast
}
ultimately have False by blast
}
ultimately show ?thesis by blast
qed

```

```

lemma cdclW-cp-tranclp-cdclW:
  cdclW-cp S S'  $\implies$  cdclW++ S S'
  apply (induct rule: cdclW-cp.induct)
  by (meson cdclW.conflict cdclW.propagate tranclp.r-into-trancl tranclp.trancl-into-trancl)+

```

```

lemma tranclp-cdclW-cp-tranclp-cdclW:
  cdclW-cp++ S S'  $\implies$  cdclW++ S S'
  apply (induct rule: tranclp.induct)
  apply (simp add: cdclW-cp-tranclp-cdclW)
  by (meson cdclW-cp-tranclp-cdclW tranclp-trans)

```

```

lemma cdclW-stgy-tranclp-cdclW:
  cdclW-stgy S S'  $\implies$  cdclW++ S S'
proof (induct rule: cdclW-stgy.induct)
  case conflict'
  then show ?case
    unfolding full1-def by (simp add: tranclp-cdclW-cp-tranclp-cdclW)
next
  case (other' S' S'')
  then have S' = S''  $\vee$  cdclW-cp++ S' S''
    by (simp add: rtranclp-unfold full-def)
  then show ?case
    using other' by (meson cdclW-ops.other cdclW-ops-axioms tranclp.r-into-trancl
      tranclp-cdclW-cp-tranclp-cdclW tranclp-trans)
qed

```

```

lemma tranclp-cdclW-stgy-tranclp-cdclW:
  cdclW-stgy++ S S'  $\implies$  cdclW++ S S'
  apply (induct rule: tranclp.induct)
  using cdclW-stgy-tranclp-cdclW apply blast
  by (meson cdclW-stgy-tranclp-cdclW tranclp-trans)

```

```

lemma rtranclp-cdclW-stgy-rtranclp-cdclW:
  cdclW-stgy** S S'  $\implies$  cdclW** S S'
  using rtranclp-unfold[of cdclW-stgy S S'] tranclp-cdclW-stgy-tranclp-cdclW[of S S'] by auto

```

```

lemma cdclW-o-conflict-is-false-with-level-inv:
  assumes
    cdclW-o S S' and

```

lev: *cdcl_W-M-level-inv S* **and**
confl-inv: *conflict-is-false-with-level S* **and**
n-d: *distinct-cdcl_W-state S* **and**
conflicting: *cdcl_W-conflicting S*
shows *conflict-is-false-with-level S'*
using *assms(1,2)*
proof (*induct rule: cdcl_W-o-induct-lev2*)
case (*resolve L C M D T*) **note** *tr-S = this(1)* **and** *confl = this(2)* **and** *T = this(4)*
have $-L \notin \# D$ **using** *n-d confl unfolding distinct-cdcl_W-state-def distinct-mset-def* **by** *auto*
moreover **have** $L \notin \# D$
proof (*rule ccontr*)
assume $\neg ?thesis$
moreover **have** *Propagated L (C + {#L#}) # M* \models_{as} *CNot D*
using *conflicting confl tr-S unfolding cdcl_W-conflicting-def* **by** *auto*
ultimately **have** $-L \in \text{lits-of } (\text{Propagated L } (C + \{ \#L\# \})) \# M$
using *in-CNot-implies-uminus(2)* **by** *blast*
moreover **have** *no-dup (Propagated L (C + {#L#})) # M*
using *lev tr-S unfolding cdcl_W-M-level-inv-def* **by** *auto*
ultimately **show** *False* **unfolding** *lits-of-def* **by** (*metis consistent-interp-def image-eqI*
list.set-intros(1) lits-of-def marked-lit.sel(2) distinctconsistent-interp)
qed
ultimately
have *g-D: get-maximum-level D (Propagated L (C + {#L#})) # M*
 $= \text{get-maximum-level } D \ M$
proof –
have $\forall a \ f \ L. ((a::'v) \in f \ 'L) = (\exists l. (l::'v \text{ literal}) \in L \wedge a = f \ l)$
by *blast*
then **show** *?thesis*
using *get-maximum-level-skip-first[of L D (C + {#L#}) M] unfolding atms-of-def*
by (*metis (no-types) $\langle - L \notin \# D \rangle \langle L \notin \# D \rangle \text{atm-of-eq-atm-of mem-set-mset-iff}$*)
qed
{ **assume**
get-maximum-level D (Propagated L (C + {#L#})) # M = backtrack-lvl S **and**
backtrack-lvl S > 0
then **have** *D: get-maximum-level D M = backtrack-lvl S* **unfolding** *g-D* **by** *blast*
then **have** *?case*
using *tr-S $\langle \text{backtrack-lvl } S > 0 \rangle \text{get-maximum-level-exists-lit[of backtrack-lvl } S \ D \ M]$ T*
by *auto*
}
moreover **{**
assume [*simp*]: *backtrack-lvl S = 0*
have $\bigwedge L. \text{get-level } L \ M = 0$
proof –
fix *L*
have *atm-of L \notin atm-of ' (lits-of M) \implies get-level L M = 0* **by** *auto*
moreover **{**
assume *atm-of L \in atm-of ' (lits-of M)*
have *g-r: get-all-levels-of-marked M = rev [Suc 0.. $\text{Suc } (\text{backtrack-lvl } S)$]*
using *lev tr-S unfolding cdcl_W-M-level-inv-def* **by** *auto*
have *Max (insert 0 (set (get-all-levels-of-marked M))) = (backtrack-lvl S)*
unfolding *g-r* **by** (*simp add: Max-n-upt*)
then **have** *get-level L M = 0*
using *get-maximum-possible-level-ge-get-level[of L M]*
unfolding *get-maximum-possible-level-max-get-all-levels-of-marked* **by** *auto*
}

```

    }
    ultimately show get-level  $L\ M = 0$  by blast
  qed
  then have ?case using get-maximum-level-exists-lit-of-max-level[of  $D \# \cup C\ M$ ] tr-S T
    by (auto simp: Bex-mset-def)
}
ultimately show ?case using resolve.hyps(3) by blast
next
case (skip  $L\ C'\ M\ D\ T$ ) note tr-S = this(1) and  $D = \textit{this}(2)$  and  $T = \textit{this}(5)$ 
then obtain La where  $La \in \# D$  and get-level  $La\ (\textit{Propagated}\ L\ C' \# M) = \textit{backtrack-lvl}\ S$ 
  using skip confl-inv by auto
moreover
  have atm-of  $La \neq \textit{atm-of}\ L$ 
  proof (rule ccontr)
    assume  $\neg ?\textit{thesis}$ 
    then have  $La: La = L$  using  $\langle La \in \# D \rangle \langle - L \notin \# D \rangle$  by (auto simp add: atm-of-eq-atm-of)
    have  $\textit{Propagated}\ L\ C' \# M \models_{as} CNot\ D$ 
      using conflicting tr-S D unfolding cdclW-conflicting-def by auto
    then have  $-L \in \textit{lits-of}\ M$ 
      using  $\langle La \in \# D \rangle$  in-CNot-implies-uminus(2)[of  $D\ L\ \textit{Propagated}\ L\ C' \# M$ ] unfolding La
      by auto
    then show False using lev tr-S unfolding cdclW-M-level-inv-def consistent-interp-def by auto
  qed
  then have get-level  $La\ (\textit{Propagated}\ L\ C' \# M) = \textit{get-level}\ La\ M$  by auto
  ultimately show ?case using  $D\ \textit{tr-S}\ T$  by auto
qed (auto split: split-if-asm simp: cdclW-M-level-inv-decomp)

```

17.6.5 Strong completeness

lemma *cdcl_W-cp-propagate-confl*:

assumes *cdcl_W-cp* $S\ T$
 shows *propagate*** $S\ T \vee (\exists S'. \textit{propagate**}\ S\ S' \wedge \textit{conflict}\ S'\ T)$
 using *assms* by *induction blast+*

lemma *rtranclp-cdcl_W-cp-propagate-confl*:

assumes *cdcl_W-cp*** $S\ T$
 shows *propagate*** $S\ T \vee (\exists S'. \textit{propagate**}\ S\ S' \wedge \textit{conflict}\ S'\ T)$
 by (simp add: *assms* *rtranclp-cdcl_W-cp-propa-or-propa-confl*)

lemma *cdcl_W-cp-propagate-completeness*:

assumes $MN: \textit{set}\ M \models_s \textit{set-mset}\ N$ and
cons: *consistent-interp* (*set* M) and
tot: *total-over-m* (*set* M) (*set-mset* N) and
lits-of (*trail* S) $\subseteq \textit{set}\ M$ and
init-clss $S = N$ and
*propagate*** $S\ S'$ and
learned-clss $S = \{\#\}$
 shows $\textit{length}\ (\textit{trail}\ S) \leq \textit{length}\ (\textit{trail}\ S') \wedge \textit{lits-of}\ (\textit{trail}\ S') \subseteq \textit{set}\ M$
 using *assms*(6,4,5,7)

proof (*induction* rule: *rtranclp-induct*)

case *base*

then show ?*case* by auto

next

case (*step* $Y\ Z$)

note $st = \textit{this}(1)$ and *propa* = *this*(2) and *IH* = *this*(3) and $\textit{lits}' = \textit{this}(4)$ and *NS* = *this*(5) and
learned = *this*(6)

then have $len: length (trail S) \leq length (trail Y)$ **and** $LM: lits-of (trail Y) \subseteq set M$
by *blast+*

obtain $M' N' U k C L$ **where**
 $Y: state Y = (M', N', U, k, C-True)$ **and**
 $Z: state Z = (Propagated L (C + \{\#L\}) \# M', N', U, k, C-True)$ **and**
 $C: C + \{\#L\} \in \# clauses Y$ **and**
 $M'-C: M' \models_{as} CNot C$ **and**
 $undefined-lit (trail Y) L$
using *propa* **by** *auto*

have $init-clss S = init-clss Y$
using *st* **by** *induction auto*

then have $[simp]: N' = N$ **using** *NS Y Z* **by** *simp*

have $learned-clss Y = \{\#\}$
using *st learned* **by** *induction auto*

then have $[simp]: U = \{\#\}$ **using** *Y* **by** *auto*

have $set M \models_s CNot C$
using $M'-C LM Y$ **unfolding** *true-annot-def Ball-def true-annot-def true-clss-def true-clss-def*
by *force*

moreover
have $set M \models C + \{\#L\}$
using *MN C learned Y* **unfolding** *true-clss-def clauses-def*
by $(metis NS \langle init-clss S = init-clss Y \rangle \langle learned-clss Y = \{\#\} \rangle add.right-neutral mem-set-mset-iff)$

ultimately have $L \in set M$ **by** $(simp add: cons consistent-CNot-not)$

then show *?case* **using** *LM len Y Z* **by** *auto*

qed

lemma *completeness-is-a-full1-propagation:*

fixes $S :: 'st$ **and** $M :: 'v$ *literal list*
assumes $MN: set M \models_s set-mset N$
and $cons: consistent-interp (set M)$
and $tot: total-over-m (set M) (set-mset N)$
and $alien: no-strange-atm S$
and $learned: learned-clss S = \{\#\}$
and $clsS[simp]: init-clss S = N$
and $lits: lits-of (trail S) \subseteq set M$
shows $\exists S'. propagate^{**} S S' \wedge full cdcl_W-cp S S'$

proof –

obtain S' **where** $full: full cdcl_W-cp S S'$
using *always-exists-full-cdcl_W-cp-step alien* **by** *blast*

then consider $(propa) propagate^{**} S S'$
 $| (confl) \exists X. propagate^{**} S X \wedge conflict X S'$
using *rtrancp-cdcl_W-cp-propagate-confl* **unfolding** *full-def* **by** *blast*

then show *?thesis*
proof *cases*
case *propa* **then show** *?thesis* **using** *full* **by** *blast*

next
case *confl*
then obtain X **where**
 $X: propagate^{**} S X$ **and**
 $Xconf: conflict X S'$
by *blast*
have $clsX: init-clss X = init-clss S$
using X **by** *induction auto*

have *learnedX*: *learned-clss* $X = \{\#\}$ **using** X *learned* **by** *induction auto*
obtain E **where**
 E : $E \in \#$ *init-clss* $X +$ *learned-clss* X **and**
 $\text{Not-}E$: $\text{trail } X \models_{\text{as}} \text{CNot } E$
 using $X\text{conf}$ **by** (*auto simp add: conflict.simps clauses-def*)
have *lits-of* ($\text{trail } X$) \subseteq *set* M
 using *cdcl_W-cp-propagate-completeness*[*OF assms(1-3) lits - X learned*] *learned* **by** *auto*
then have MNE : $\text{set } M \models_s \text{CNot } E$
 using $\text{Not-}E$
 by (*fastforce simp add: true-annots-def true-annot-def true-clss-def true-cls-def*)
have $\neg \text{set } M \models_s \text{set-mset } N$
 using E *consistent-CNot-not*[*OF cons MNE*]
 unfolding *learnedX true-clss-def* **unfolding** *clsX clsS* **by** *auto*
then show *?thesis* **using** MN **by** *blast*
qed
qed

See also *cdcl_W-cp*** $?S ?S' \implies \exists M. \text{trail } ?S' = M @ \text{trail } ?S \wedge (\forall l \in \text{set } M. \neg \text{is-marked } l)$

lemma *rtrancp-propagate-is-trail-append*:
*propagate*** $S T \implies \exists c. \text{trail } T = c @ \text{trail } S$
by (*induction rule: rtrancp-induct*) *auto*

lemma *rtrancp-propagate-is-update-trail*:
*propagate*** $S T \implies \text{cdcl}_W\text{-}M\text{-level-inv } S \implies T \sim \text{delete-trail-and-rebuild } (\text{trail } T) S$
proof (*induction rule: rtrancp-induct*)

case *base*
then show *?case* **unfolding** *state-eq-def* **by** (*auto simp: cdcl_W-M-level-inv-decomp*)
next
case (*step* $T U$) **note** $IH = \text{this}(3)[\text{OF this}(4)]$
moreover have *cdcl_W-M-level-inv* U
 using *rtrancp-cdcl_W-consistent-inv* $\langle \text{propagate** } S T \rangle \langle \text{propagate } T U \rangle$
 rtrancp-mono[*of propagate cdcl_W*] *cdcl_W-cp-consistent-inv* *propagate'*
 rtrancp-propagate-is-rtrancp-cdcl_W *step.premis* **by** *blast*
then have *no-dup* ($\text{trail } U$) **unfolding** *cdcl_W-M-level-inv-def* **by** *auto*
ultimately show *?case* **using** $\langle \text{propagate } T U \rangle$ **unfolding** *state-eq-def* **by** *fastforce*
qed

lemma *cdcl_W-stgy-strong-completeness-n*:

assumes
 MN : $\text{set } M \models_s \text{set-mset } N$ **and**
 cons : *consistent-interp* ($\text{set } M$) **and**
 tot : *total-over-m* ($\text{set } M$) ($\text{set-mset } N$) **and**
 atm-incl : *atm-of* ' ($\text{set } M$) \subseteq *atms-of-msu* N **and**
 distM : *distinct* M **and**
 length : $n \leq \text{length } M$

shows

$\exists M' k S. \text{length } M' \geq n \wedge$
 $\text{lits-of } M' \subseteq \text{set } M \wedge$
 $\text{no-dup } M' \wedge$
 $S \sim \text{update-backtrack-lvl } k (\text{append-trail } (\text{rev } M') (\text{init-state } N)) \wedge$
 $\text{cdcl}_W\text{-stgy** } (\text{init-state } N) S$

using *length*

proof (*induction n*)

case 0

have *update-backtrack-lvl* 0 ($\text{append-trail } (\text{rev } []) (\text{init-state } N)$) $\sim \text{init-state } N$


```

  by (auto simp: state-eq-def simp del: state-simp)
moreover have
  0 ≤ length [] and
  lits-of [] ⊆ set M and
  cdclW-stgy** (init-state N) (init-state N)
  and no-dup []
  by (auto simp: state-eq-def simp del: state-simp)
ultimately show ?case using state-eq-sym by blast
next
case (Suc n) note IH = this(1) and n = this(2)
then obtain M' k S where
  l-M': length M' ≥ n and
  M': lits-of M' ⊆ set M and
  n-d[simp]: no-dup M' and
  S: S ∼ update-backtrack-lvl k (append-trail (rev M') (init-state N)) and
  st: cdclW-stgy** (init-state N) S
  by auto
have
  M: cdclW-M-level-inv S and
  alien: no-strange-atm S
  using rtrancp-cdclW-consistent-inv[OF rtrancp-cdclW-stgy-rtrancp-cdclW[OF st]]
  rtrancp-cdclW-no-strange-atm-inv[OF rtrancp-cdclW-stgy-rtrancp-cdclW[OF st]]
  S unfolding state-eq-def cdclW-M-level-inv-def no-strange-atm-def by auto
{ assume no-step: ¬no-step propagate S

  obtain S' where S': propagate** S S' and full: full cdclW-cp S S'
  using completeness-is-a-full1-propagation[OF assms(1-3), of S] alien M' S by auto
  have lev: cdclW-M-level-inv S'
  using M S' rtrancp-cdclW-consistent-inv rtrancp-propagate-is-rtrancp-cdclW by blast
  then have n-d'[simp]: no-dup (trail S')
  unfolding cdclW-M-level-inv-def by auto
  have length (trail S) ≤ length (trail S') ∧ lits-of (trail S') ⊆ set M
  using S' full cdclW-cp-propagate-completeness[OF assms(1-3), of S] M' S by auto
  moreover
  have full: full1 cdclW-cp S S'
  using full no-step no-step-cdclW-cp-no-conflict-no-propagate(2) unfolding full1-def full-def
  rtrancp-unfold by blast
  then have cdclW-stgy S S' by (simp add: cdclW-stgy.conflict')
  moreover
  have propa: propagate++ S S' using S' full unfolding full1-def by (metis rtrancpD trancpD)
  have trail S = M' using S by auto
  with propa have length (trail S') > n
  using l-M' propa by (induction rule: trancp.induct) auto
  moreover
  have stS': cdclW-stgy** (init-state N) S'
  using st cdclW-stgy.conflict'[OF full] by auto
  then have init-clss S' = N using stS' rtrancp-cdclW-stgy-no-more-init-clss by fastforce
  moreover
  have
    [simp]: learned-clss S' = {#} and
    [simp]: init-clss S' = init-clss S and
    [simp]: conflicting S' = C-True
  using trancp-into-rtrancp[OF ⟨propagate++ S S'⟩] S
  rtrancp-propagate-is-update-trail[of S S'] S M unfolding state-eq-def by simp-all
  have S-S': S' ∼ update-backtrack-lvl (backtrack-lvl S')

```

```

    (append-trail (rev (trail S')) (init-state N)) using S
  by (auto simp: state-eq-def simp del: state-simp)
have cdclW-stgy** (init-state (init-clss S')) S'
  apply (rule rtranclp.rtrancl-into-rtrancl)
  using st unfolding ⟨init-clss S' = N⟩ apply simp
  using ⟨cdclW-stgy S S'⟩ by simp
ultimately have ?case
  apply -
  apply (rule exI[of - trail S'], rule exI[of - backtrack-lvl S'], rule exI[of - S'])
  using S-S' by (auto simp: state-eq-def simp del: state-simp)
}
moreover {
  assume no-step: no-step propagate S
  have ?case
  proof (cases length M' ≥ Suc n)
    case True
    then show ?thesis using l-M' M' st M alien S by fastforce
  next
    case False
    then have n': length M' = n using l-M' by auto
    have no-confli: no-step conflict S
    proof -
      { fix D
        assume D ∈# N and M' ⊨as CNot D
        then have set M ⊨ D using MN unfolding true-clss-def by auto
        moreover have set M ⊨s CNot D
          using ⟨M' ⊨as CNot D⟩ M'
          by (metis le-iff-sup true-annots-true-clss true-clss-union-increase)
        ultimately have False using cons consistent-CNot-not by blast
      }
    then show ?thesis using S by (auto simp add: conflict.simps true-clss-def)
  qed
  have lenM: length M = card (set M) using distM by (induction M) auto
  have no-dup M' using S M unfolding cdclW-M-level-inv-def by auto
  then have card (lits-of M') = length M'
    by (induction M') (auto simp add: lits-of-def card-insert-if)
  then have lits-of M' ⊂ set M
    using n M' n' lenM by auto
  then obtain m where m: m ∈ set M and undef-m: m ∉ lits-of M' by auto
  moreover have undef: undefined-lit M' m
    using M' Marked-Propagated-in-iff-in-lits-of calculation(1,2) cons
    consistent-interp-def by blast
  moreover have atm-of m ∈ atms-of-msu (init-clss S)
    using atm-incl calculation S by auto
  ultimately
    have dec: decide S (cons-trail (Marked m (k+1)) (incr-lvl S))
      using decide.intros[of S rev M' N - k m
        cons-trail (Marked m (k + 1)) (incr-lvl S)] S
      by auto
  let ?S' = cons-trail (Marked m (k+1)) (incr-lvl S)
  have lits-of (trail ?S') ⊆ set M using m M' S undef by auto
  moreover have no-strange-atm ?S'
    using alien dec M by (meson cdclW-no-strange-atm-inv decide other)
  ultimately obtain S'' where S'': propagate** ?S' S'' and full: full cdclW-cp ?S' S''
    using completeness-is-a-full1-propagation[OF assms(1-3), of ?S'] S undef by auto

```

```

have  $cdcl_W$ - $M$ -level-inv  $?S'$ 
  using  $M$  dec rtrancp-mono[of decide  $cdcl_W$ ] by (meson  $cdcl_W$ -consistent-inv decide other)
then have  $lev''$ :  $cdcl_W$ - $M$ -level-inv  $S''$ 
  using  $S''$  rtrancp- $cdcl_W$ -consistent-inv rtrancp-propagate-is-rtrancp- $cdcl_W$  by blast
then have  $n-d''$ : no-dup (trail  $S''$ )
  unfolding  $cdcl_W$ - $M$ -level-inv-def by auto
have length (trail  $?S'$ )  $\leq$  length (trail  $S''$ )  $\wedge$  lits-of (trail  $S''$ )  $\subseteq$  set  $M$ 
  using  $S''$  full  $cdcl_W$ -cp-propagate-completeness[OF  $assms(1-3)$ , of  $?S' S''$ ]  $m M' S$  undef
  by simp
then have  $Suc\ n \leq$  length (trail  $S''$ )  $\wedge$  lits-of (trail  $S''$ )  $\subseteq$  set  $M$ 
  using  $l-M' S$  undef by auto
moreover
  have  $cdcl_W$ - $M$ -level-inv (cons-trail (Marked  $m$  ( $Suc$  (backtrack-lvl  $S$ )))
    (update-backtrack-lvl ( $Suc$  (backtrack-lvl  $S$ ))  $S$ ))
    using  $S$   $cdcl_W$ - $M$ -level-inv (cons-trail (Marked  $m$  ( $k + 1$ )) (incr-lvl  $S$ )) by auto
  then have  $S''$ :  $S'' \sim$  update-backtrack-lvl (backtrack-lvl  $S''$ )
    (append-trail (rev (trail  $S''$ )) (init-state  $N$ ))
    using rtrancp-propagate-is-update-trail[OF  $S''$ ]  $S$  undef  $n-d''$   $lev''$ 
    by (auto simp del: state-simp simp: state-eq-def )
  then have  $cdcl_W$ -stgy** (init-state  $N$ )  $S''$ 
    using  $cdcl_W$ -stgy.intros(2)[OF decide[OF dec] - full] no-step no-confl  $st$ 
    by (auto simp:  $cdcl_W$ -cp.simps)
  ultimately show  $?thesis$  using  $S''$   $n-d''$  by blast
qed
}
ultimately show  $?case$  by blast
qed

```

lemma $cdcl_W$ -stgy-strong-completeness:

```

assumes  $MN$ : set  $M \models_s$  set-mset  $N$ 
and  $cons$ : consistent-interp (set  $M$ )
and  $tot$ : total-over- $m$  (set  $M$ ) (set-mset  $N$ )
and  $atm$ -incl: atm-of ' (set  $M$ )  $\subseteq$  atms-of-msu  $N$ 
and  $distM$ : distinct  $M$ 

```

shows

```

 $\exists M' k S.$ 
  lits-of  $M' =$  set  $M \wedge$ 
   $S \sim$  update-backtrack-lvl  $k$  (append-trail (rev  $M'$ ) (init-state  $N$ ))  $\wedge$ 
   $cdcl_W$ -stgy** (init-state  $N$ )  $S \wedge$ 
  final- $cdcl_W$ -state  $S$ 

```

proof –

```

from  $cdcl_W$ -stgy-strong-completeness-n[OF  $assms$ , of length  $M$ ]
obtain  $M' k T$  where
   $l$ : length  $M \leq$  length  $M'$  and
   $M'-M$ : lits-of  $M' \subseteq$  set  $M$  and
  no-dup: no-dup  $M'$  and
   $T$ :  $T \sim$  update-backtrack-lvl  $k$  (append-trail (rev  $M'$ ) (init-state  $N$ )) and
   $st$ :  $cdcl_W$ -stgy** (init-state  $N$ )  $T$ 
  by auto
have card (set  $M$ ) = length  $M$  using  $distM$  by (simp add: distinct-card)
moreover
  have  $cdcl_W$ - $M$ -level-inv  $T$ 
    using rtrancp- $cdcl_W$ -stgy-consistent-inv[OF  $st$ ]  $T$  by auto
  then have card (set ((map ( $\lambda l.$  atm-of (lit-of  $l$ ))  $M'$ ))) = length  $M'$ 
    using distinct-card no-dup by fastforce

```

```

moreover have card (lits-of  $M'$ ) = card (set ((map ( $\lambda l$ . atm-of (lit-of  $l$ ))  $M'$ )))
  using no-dup unfolding lits-of-def apply (induction  $M'$ ) by (auto simp add: card-insert-if)
ultimately have card (set  $M$ )  $\leq$  card (lits-of  $M'$ ) using  $l$  unfolding lits-of-def by auto
then have set  $M$  = lits-of  $M'$ 
  using  $M'-M$  card-seteq by blast
moreover
  then have  $M' \models_{asm} N$ 
    using  $MN$  unfolding true-annots-def Ball-def true-annot-def true-clss-def by auto
  then have final-cdclW-state  $T$ 
    using  $T$  no-dup unfolding final-cdclW-state-def by auto
  ultimately show ?thesis using  $st$   $T$  by blast
qed

```

17.6.6 No conflict with only variables of level less than backtrack level

This invariant is stronger than the previous argument in the sense that it is a property about all possible conflicts.

definition no-smaller-conflict ($S::'st$) \equiv
 $(\forall M K i M' D. M' @ \text{Marked } K i \# M = \text{trail } S \longrightarrow D \in \# \text{ clauses } S$
 $\longrightarrow \neg M \models_{as} \text{CNot } D)$

lemma no-smaller-conflict-init-sate[simp]:
 no-smaller-conflict (init-state N) **unfolding** no-smaller-conflict-def **by** auto

lemma cdcl_W-o-no-smaller-conflict-inv:

```

fixes  $S S' :: 'st$ 
assumes
  cdclW-o  $S S'$  and
  lev: cdclW-M-level-inv  $S$  and
  max-lev: conflict-is-false-with-level  $S$  and
  smaller: no-smaller-conflict  $S$  and
  no-f: no-clause-is-false  $S$ 
shows no-smaller-conflict  $S'$ 
using assms(1,2) unfolding no-smaller-conflict-def
proof (induct rule: cdclW-o-induct-lev2)
case (decide  $L T$ ) note conflict = this(1) and undef = this(2) and  $T = \text{this}(4)$ 
have [simp]: clauses  $T$  = clauses  $S$ 
  using  $T$  undef by auto
show ?case
proof (intro allI impI)
  fix  $M'' K i M' Da$ 
  assume  $M'' @ \text{Marked } K i \# M' = \text{trail } T$ 
  and  $D: Da \in \# \text{ local.clauses } T$ 
  then have  $tl M'' @ \text{Marked } K i \# M' = \text{trail } S$ 
     $\vee (M'' = [] \wedge \text{Marked } K i \# M' = \text{Marked } L (\text{backtrack-lvl } S + 1) \# \text{trail } S)$ 
    using  $T$  undef by (cases  $M''$ ) auto
  moreover {
    assume  $tl M'' @ \text{Marked } K i \# M' = \text{trail } S$ 
    then have  $\neg M' \models_{as} \text{CNot } Da$ 
      using  $D T$  undef no-f conflict smaller unfolding no-smaller-conflict-def smaller by fastforce
  }
  moreover {
    assume  $\text{Marked } K i \# M' = \text{Marked } L (\text{backtrack-lvl } S + 1) \# \text{trail } S$ 
    then have  $\neg M' \models_{as} \text{CNot } Da$  using no-f  $D$  conflict  $T$  by auto
  }

```

```

    ultimately show  $\neg M' \models_{as} CNot\ Da$  by fast
  qed
next
  case resolve
  then show ?case using smaller no-f max-lev unfolding no-smaller-confl-def by auto
next
  case skip
  then show ?case using smaller no-f max-lev unfolding no-smaller-confl-def by auto
next
  case (backtrack K i M1 M2 L D T) note decomp = this(1) and confl = this(3) and undef = this(6)
    and T = this(7)
  obtain c where M: trail S = c @ M2 @ Marked K (i+1) # M1
    using decomp by auto

show ?case
proof (intro allI impI)
  fix M ia K' M' Da
  assume M' @ Marked K' ia # M = trail T
  then have tl M' @ Marked K' ia # M = M1
    using T decomp undef lev by (cases M') (auto simp: cdclW-M-level-inv-decomp)
  assume D: Da ∈ # clauses T
  moreover {
    assume Da ∈ # clauses S
    then have  $\neg M \models_{as} CNot\ Da$  using (tl M' @ Marked K' ia # M = M1) M confl undef smaller
      unfolding no-smaller-confl-def by auto
  }
  moreover {
    assume Da: Da = D + {#L#}
    have  $\neg M \models_{as} CNot\ Da$ 
    proof (rule ccontr)
      assume  $\neg$  ?thesis
      then have  $-L \in \text{ lits-of } M$  unfolding Da by auto
      then have  $-L \in \text{ lits-of } (\text{Propagated } L ((D + \{ \#L\# \})) \# M1)$ 
        using UnI2 (tl M' @ Marked K' ia # M = M1)
        by auto
      moreover
        have backtrack S
          (cons-trail (Propagated L (D + {#L#})))
          (reduce-trail-to M1 (add-learned-cls (D + {#L#})))
          (update-backtrack-lvl i (update-conflicting C-True S))))
        using backtrack.intros[of S] backtrack.hyps
        by (force simp: state-eq-def simp del: state-simp)
      then have cdclW-M-level-inv
        (cons-trail (Propagated L (D + {#L#})))
        (reduce-trail-to M1 (add-learned-cls (D + {#L#})))
        (update-backtrack-lvl i (update-conflicting C-True S))))
        using cdclW-consistent-inv[OF - lev] other[OF bj] by auto
      then have no-dup (Propagated L (D + {#L#})) # M1
        using decomp undef lev unfolding cdclW-M-level-inv-def by auto
      ultimately show False by (metis consistent-interp-def distinctconsistent-interp
        insertCI lits-of-cons marked-lit.sel(2))
    qed
  }
  ultimately show  $\neg M \models_{as} CNot\ Da$ 
    using T undef (Da = D + {#L#}  $\implies \neg M \models_{as} CNot\ Da$ ) decomp lev

```

```

      unfolding cdclW-M-level-inv-def by fastforce
    qed
  qed

lemma conflict-no-smaller-conf-inv:
  assumes conflict S S'
  and no-smaller-conf S
  shows no-smaller-conf S'
  using assms unfolding no-smaller-conf-def by fastforce

lemma propagate-no-smaller-conf-inv:
  assumes propagate: propagate S S'
  and n-l: no-smaller-conf S
  shows no-smaller-conf S'
  unfolding no-smaller-conf-def
proof (intro allI impI)
  fix M' K i M'' D
  assume M': M'' @ Marked K i # M' = trail S'
  and D ∈ # clauses S'
  obtain M N U k C L where
    S: state S = (M, N, U, k, C-True) and
    S': state S' = (Propagated L ( (C + {#L#})) # M, N, U, k, C-True) and
    C + {#L#} ∈ # clauses S and
    M ⊨as CNot C and
    undefined-lit M L
  using propagate by auto
  have tl M'' @ Marked K i # M' = trail S using M' S S'
  by (metis Pair-inject list.inject list.sel(3) marked-lit.distinct(1) self-append-conv2
    tl-append2)
  then have ¬M' ⊨as CNot D
  using ⟨D ∈ # clauses S'⟩ n-l S S' clauses-def unfolding no-smaller-conf-def by auto
  then show ¬M' ⊨as CNot D by auto
qed

lemma cdclW-cp-no-smaller-conf-inv:
  assumes propagate: cdclW-cp S S'
  and n-l: no-smaller-conf S
  shows no-smaller-conf S'
  using assms
proof (induct rule: cdclW-cp.induct)
  case (conflict' S S')
  then show ?case using conflict-no-smaller-conf-inv[of S S'] by blast
next
  case (propagate' S S')
  then show ?case using propagate-no-smaller-conf-inv[of S S'] by fastforce
qed

lemma rtrancp-cdclW-cp-no-smaller-conf-inv:
  assumes propagate: cdclW-cp** S S'
  and n-l: no-smaller-conf S
  shows no-smaller-conf S'
  using assms
proof (induct rule: rtrancp-induct)
  case base
  then show ?case by simp

```

```

next
  case (step S' S'')
  then show ?case using cdclW-cp-no-smaller-conflict-inv[of S' S''] by fast
qed

lemma tranp-cdclW-cp-no-smaller-conflict-inv:
  assumes propagate: cdclW-cp++ S S'
  and n-l: no-smaller-conflict S
  shows no-smaller-conflict S'
  using assms
proof (induct rule: tranp.induct)
  case (r-into-trancl S S')
  then show ?case using cdclW-cp-no-smaller-conflict-inv[of S S'] by blast
next
  case (trancl-into-trancl S S' S'')
  then show ?case using cdclW-cp-no-smaller-conflict-inv[of S' S''] by fast
qed

lemma full-cdclW-cp-no-smaller-conflict-inv:
  assumes full cdclW-cp S S'
  and n-l: no-smaller-conflict S
  shows no-smaller-conflict S'
  using assms unfolding full-def
  using rtranp-cdclW-cp-no-smaller-conflict-inv[of S S'] by blast

lemma full1-cdclW-cp-no-smaller-conflict-inv:
  assumes full1 cdclW-cp S S'
  and n-l: no-smaller-conflict S
  shows no-smaller-conflict S'
  using assms unfolding full1-def
  using tranp-cdclW-cp-no-smaller-conflict-inv[of S S'] by blast

lemma cdclW-stgy-no-smaller-conflict-inv:
  assumes cdclW-stgy S S'
  and n-l: no-smaller-conflict S
  and conflict-is-false-with-level S
  and cdclW-M-level-inv S
  shows no-smaller-conflict S'
  using assms
proof (induct rule: cdclW-stgy.induct)
  case (conflict' S')
  then show ?case using full1-cdclW-cp-no-smaller-conflict-inv[of S S'] by blast
next
  case (other' S' S'')
  have no-smaller-conflict S'
    using cdclW-o-no-smaller-conflict-inv[OF other'.hyps(1) other'.prems(3,2,1)]
    not-conflict-not-any-negated-init-clss other'.hyps(2) by blast
  then show ?case using full-cdclW-cp-no-smaller-conflict-inv[of S' S''] other'.hyps by blast
qed

lemma conflict-conflict-is-no-clause-is-false-test:
  assumes conflict S S'
  and (∀ D ∈# init-clss S + learned-clss S. trail S ⊨as CNot D
    → (∃ L. L ∈# D ∧ get-level L (trail S) = backtrack-lvl S))

```

shows $\forall D \in \# \text{ init-clss } S' + \text{ learned-clss } S'. \text{ trail } S' \models_{as} CNot D$
 $\longrightarrow (\exists L. L \in \# D \wedge \text{ get-level } L (\text{ trail } S') = \text{ backtrack-lvl } S')$
using *assms* **by** *auto*

lemma *is-conflicting-exists-conflict*:

assumes $\neg(\forall D \in \# \text{ init-clss } S' + \text{ learned-clss } S'. \neg \text{ trail } S' \models_{as} CNot D)$
and *conflicting* $S' = C\text{-True}$
shows $\exists S''. \text{ conflict } S' S''$
using *assms* *clauses-def* *not-conflict-not-any-negated-init-clss* **by** *fastforce*

lemma *cdcl_W-o-conflict-is-no-clause-is-false*:

fixes $S S' :: 'st$
assumes
cdcl_W-o $S S'$ **and**
lev: *cdcl_W-M-level-inv* S **and**
max-lev: *conflict-is-false-with-level* S **and**
no-f: *no-clause-is-false* S **and**
no-l: *no-smaller-conf* S
shows *no-clause-is-false* S'
 $\vee (\text{conflicting } S' = C\text{-True}$
 $\longrightarrow (\forall D \in \# \text{ clauses } S'. \text{ trail } S' \models_{as} CNot D$
 $\longrightarrow (\exists L. L \in \# D \wedge \text{ get-level } L (\text{ trail } S') = \text{ backtrack-lvl } S'))$
using *assms*(1,2)

proof (*induct* rule: *cdcl_W-o-induct-lev2*)

case (*decide* $L T$) **note** $S = \text{this}(1)$ **and** *undef* = *this*(2) **and** $T = \text{this}(4)$

show ?*case*

proof (rule *HOL.disjI2*, *clarify*)

fix D

assume $D: D \in \# \text{ clauses } T$ **and** $M\text{-}D: \text{ trail } T \models_{as} CNot D$

let ? $M = \text{ trail } S$

let ? $M' = \text{ trail } T$

let ? $k = \text{ backtrack-lvl } S$

have $\neg ?M \models_{as} CNot D$

using *no-f* $D S T \text{ undef}$ **by** *auto*

have $-L \in \# D$

proof (rule *ccontr*)

assume $\neg ?thesis$

have ? $M \models_{as} CNot D$

unfolding *true-annots-def* *Ball-def* *true-annot-def* *CNot-def* *true-cls-def*

proof (*intro* *allI* *impI*)

fix x

assume $x: x \in \{\{\# - L\# \} \mid L. L \in \# D\}$

then obtain L' **where** $L': x = \{\# - L'\# \}$ $L' \in \# D$ **by** *auto*

obtain L'' **where** $L'' \in \# x$ **and** *lits-of* (*Marked* L ($?k + 1$) $\#$? M) $\models_l L''$

using $M\text{-}D x T \text{ undef}$ **unfolding** *true-annots-def* *Ball-def* *true-annot-def* *CNot-def* *true-cls-def* *Bex-mset-def* **by** *auto*

show $\exists L \in \# x. \text{ lits-of } ?M \models_l L$ **unfolding** *Bex-mset-def*

by (*metis* $\langle - L \notin \# D \rangle \langle L'' \in \# x \rangle L' \langle \text{ lits-of } (\text{Marked } L (\text{?k} + 1) \# ?M) \models_l L' \rangle$
count-single *insertE* *less-numeral-extra*(3) *lits-of-cons* *marked-lit.sel*(1)
true-lit-def *uminus-of-uminus-id*)

qed

then show *False* **using** $\langle \neg ?M \models_{as} CNot D \rangle$ **by** *auto*

qed

have *atm-of* $L \notin \text{ atm-of } ' (\text{ lits-of } ?M)$


```

    using undef defined-lit-map unfolding lits-of-def by fastforce
  then have get-level  $(-L)$  (Marked  $L$   $(?k + 1) \# ?M$ ) =  $?k + 1$  by simp
  then show  $\exists La. La \in \# D \wedge \text{get-level } La \text{ } ?M'$ 
    = backtrack-lvl  $T$ 
    using  $\langle -L \in \# D \rangle T$  undef by auto
qed
next
case resolve
then show  $?case$  by auto
next
case skip
then show  $?case$  by auto
next
case (backtrack  $K i M1 M2 L D T$ ) note  $decomp = \text{this}(1)$  and  $undef = \text{this}(6)$  and  $T = \text{this}(7)$ 
show  $?case$ 
proof (rule HOL.disjI2, clarify)
  fix  $Da$ 
  assume  $Da$ :  $Da \in \# \text{ clauses } T$ 
  and  $M-D$ :  $\text{trail } T \models_{as} CNot \text{ } Da$ 
  obtain  $c$  where  $M$ :  $\text{trail } S = c @ M2 @ \text{Marked } K (i + 1) \# M1$ 
  using  $decomp$  by auto
  have  $tr-T$ :  $\text{trail } T = \text{Propagated } L (D + \{\#L\# \}) \# M1$ 
  using  $T$   $decomp$  undef lev by (auto simp:  $cdcl_W$ - $M$ -level-inv-decomp)
  have backtrack  $S T$ 
  using backtrack.intros backtrack.hyps  $T$  by (force simp del: state-simp simp: state-eq-def)
  then have  $lev'$ :  $cdcl_W$ - $M$ -level-inv  $T$ 
  using  $cdcl_W$ -consistent-inv lev other by blast
  then have  $- L \notin \text{lits-of } M1$ 
  unfolding  $cdcl_W$ - $M$ -level-inv-def lits-of-def
  proof -
    have consistent-interp ( $\text{lits-of } (\text{trail } S) \wedge \text{no-dup } (\text{trail } S)$ )
       $\wedge \text{backtrack-lvl } S = \text{length } (\text{get-all-levels-of-marked } (\text{trail } S))$ 
       $\wedge \text{get-all-levels-of-marked } (\text{trail } S)$ 
      =  $\text{rev } [1..<1 + \text{length } (\text{get-all-levels-of-marked } (\text{trail } S))]$ 
    using lev  $cdcl_W$ - $M$ -level-inv-def by blast
    then show  $- L \notin \text{lit-of ' set } M1$ 
    by (metis (no-types) One-nat-def add.right-neutral add-Suc-right
      atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set backtrack.hyps(2)
       $cdcl_W$ -ops.backtrack-lit-skipped  $cdcl_W$ -ops-axioms  $decomp$  lits-of-def)
  qed
{ assume  $Da \in \# \text{ clauses } S$ 
  then have  $\neg M1 \models_{as} CNot \text{ } Da$  using  $no-l M$  unfolding no-smaller-confl-def by auto
}
moreover {
  assume  $Da$ :  $Da = D + \{\#L\# \}$ 
  have  $\neg M1 \models_{as} CNot \text{ } Da$  using  $\langle - L \notin \text{lits-of } M1 \rangle$  unfolding  $Da$  by simp
}
ultimately have  $\neg M1 \models_{as} CNot \text{ } Da$ 
  using  $Da T$  undef  $decomp$  lev by (fastforce simp:  $cdcl_W$ - $M$ -level-inv-decomp)
then have  $-L \in \# Da$ 
  using  $M-D \langle - L \notin \text{lits-of } M1 \rangle$  in-CNot-implies-uminus(2)
  true-annots-CNot-lit-of-notin-skip  $T$  unfolding  $tr-T$ 
  by (smt insert-iff lits-of-cons marked-lit.sel(2))
have  $g-M1$ :  $\text{get-all-levels-of-marked } M1 = \text{rev } [1..<i+1]$ 
  using lev  $lev' T$   $decomp$  undef unfolding  $cdcl_W$ - $M$ -level-inv-def by auto

```

```

have no-dup (Propagated L (D + {#L#}) # M1)
  using lev lev' T decomp undef unfolding cdclW-M-level-inv-def by auto
then have L: atm-of L ∉ atm-of ' lits-of M1 unfolding lits-of-def by auto
have get-level (−L) (Propagated L ((D + {#L#})) # M1) = i
  using get-level-get-rev-level-get-all-levels-of-marked[OF L,
    of [Propagated L ((D + {#L#}))]]
  by (simp add: g-M1 split: if-splits)
then show ∃ La. La ∈# Da ∧ get-level La (trail T) = backtrack-lvl T
  using (−L ∈# Da) T decomp undef lev by (auto simp: cdclW-M-level-inv-def)
qed
qed

lemma full1-cdclW-cp-exists-conflict-decompose:
  assumes confl: ∃ D ∈ #clauses S. trail S ⊨as CNot D
  and full: full cdclW-cp S U
  and no-confl: conflicting S = C-True
  shows ∃ T. propagate** S T ∧ conflict T U
proof −
  consider (propa) propagate** S U
    | (confl) T where propagate** S T and conflict T U
  using full unfolding full-def by (blast dest: rtranclp-cdclW-cp-propa-or-propa-confl)
then show ?thesis
proof cases
  case confl
  then show ?thesis by blast
next
  case propa
  then have conflicting U = C-True
    using no-confl by induction auto
  moreover have [simp]: learned-clss U = learned-clss S and
    [simp]: init-clss U = init-clss S
    using propa by induction auto
  moreover
  obtain D where D: D ∈ #clauses U and
    trS: trail S ⊨as CNot D
    using confl clauses-def by auto
  obtain M where M: trail U = M @ trail S
    using full rtranclp-cdclW-cp-dropWhile-trail unfolding full-def by meson
  have tr-U: trail U ⊨as CNot D
    apply (rule true-annots-mono)
    using trS unfolding M by simp-all
  have ∃ V. conflict U V
    using (conflicting U = C-True) D clauses-def not-conflict-not-any-negated-init-clss tr-U
    by blast
  then have False using full cdclW-cp.conflict' unfolding full-def by blast
  then show ?thesis by fast
qed
qed

lemma full1-cdclW-cp-exists-conflict-full1-decompose:
  assumes confl: ∃ D ∈ #clauses S. trail S ⊨as CNot D
  and full: full cdclW-cp S U
  and no-confl: conflicting S = C-True
  shows ∃ T D. propagate** S T ∧ conflict T U
    ∧ trail T ⊨as CNot D ∧ conflicting U = C-Clause D ∧ D ∈ #clauses S

```

proof –
obtain T **where** propa : $\text{propagate}^{**} S T$ **and** conf : $\text{conflict} T U$
using $\text{full1-cdcl}_W\text{-cp-exists-conflict-decompose}[OF \text{ assms}]$ **by** blast
have p : $\text{learned-clss } T = \text{learned-clss } S \text{ init-clss } T = \text{init-clss } S$
using propa **by** induction auto
have c : $\text{learned-clss } U = \text{learned-clss } T \text{ init-clss } U = \text{init-clss } T$
using conf **by** induction auto
obtain D **where** $\text{trail } T \models_{as} CNot D \wedge \text{conflicting } U = C\text{-Clause } D \wedge D \in \# \text{ clauses } S$
using $\text{conf } p c$ **by** $(\text{fastforce simp: clauses-def})$
then show $?thesis$
using propa conf **by** blast
qed

lemma $\text{cdcl}_W\text{-stgy-no-smaller-conf}$:

assumes $\text{cdcl}_W\text{-stgy } S S'$
and $n\text{-l: no-smaller-conf } S$
and $\text{conflict-is-false-with-level } S$
and $\text{cdcl}_W\text{-M-level-inv } S$
and $\text{no-clause-is-false } S$
and $\text{distinct-cdcl}_W\text{-state } S$
and $\text{cdcl}_W\text{-conflicting } S$
shows $\text{no-smaller-conf } S'$
using assms

proof ($\text{induct rule: cdcl}_W\text{-stgy.induct}$)

case $(\text{conflict}' S')$

show $\text{no-smaller-conf } S'$

using $\text{conflict}'.\text{hyps conflict}'.\text{prems}(1)$ $\text{full1-cdcl}_W\text{-cp-no-smaller-conf-inv}$ **by** blast

next

case $(\text{other}' S' S'')$

have lev' : $\text{cdcl}_W\text{-M-level-inv } S'$

using $\text{cdcl}_W\text{-consistent-inv other other}'.\text{hyps}(1)$ $\text{other}'.\text{prems}(3)$ **by** blast

show $\text{no-smaller-conf } S''$

using $\text{cdcl}_W\text{-stgy-no-smaller-conf-inv}[OF \text{ cdcl}_W\text{-stgy.other}'[OF \text{ other}'.\text{hyps}(1-3)]]$
 $\text{other}'.\text{prems}(1-3)$ **by** blast

qed

lemma $\text{cdcl}_W\text{-stgy-ex-lit-of-max-level}$:

assumes $\text{cdcl}_W\text{-stgy } S S'$
and $n\text{-l: no-smaller-conf } S$
and $\text{conflict-is-false-with-level } S$
and $\text{cdcl}_W\text{-M-level-inv } S$
and $\text{no-clause-is-false } S$
and $\text{distinct-cdcl}_W\text{-state } S$
and $\text{cdcl}_W\text{-conflicting } S$
shows $\text{conflict-is-false-with-level } S'$
using assms

proof ($\text{induct rule: cdcl}_W\text{-stgy.induct}$)

case $(\text{conflict}' S')$

have $\text{no-smaller-conf } S'$

using $\text{conflict}'.\text{hyps conflict}'.\text{prems}(1)$ $\text{full1-cdcl}_W\text{-cp-no-smaller-conf-inv}$ **by** blast

moreover have $\text{conflict-is-false-with-level } S'$

using $\text{conflict}'.\text{hyps conflict}'.\text{prems}(2-4)$

$\text{rtranclp-cdcl}_W\text{-co-conflict-ex-lit-of-max-level}[of S S']$

unfolding $\text{full-def full1-def rtranclp-unfold}$ **by** blast

then show $?case$ **by** blast

```

next
case (other' S' S'')
have lev': cdclW-M-level-inv S'
  using cdclW-consistent-inv other other'.hyps(1) other'.prems(3) by blast
moreover
have no-clause-is-false S'
  ∨ (conflicting S' = C-True → (∀ D ∈ # clauses S'. trail S' ⊨as CNot D
    → (∃ L. L ∈ # D ∧ get-level L (trail S') = backtrack-lvl S')))
  using cdclW-o-conflict-is-no-clause-is-false[of S S'] other'.hyps(1) other'.prems(1-4) by fast
moreover {
  assume no-clause-is-false S'
  {
    assume conflicting S' = C-True
    then have conflict-is-false-with-level S' by auto
    moreover have full cdclW-cp S' S''
      by (metis (no-types) other'.hyps(3))
    ultimately have conflict-is-false-with-level S''
      using rtrancp-cdclW-co-conflict-ex-lit-of-max-level[of S' S''] lev' ⟨no-clause-is-false S'⟩
      by blast
  }
  moreover
  {
    assume c: conflicting S' ≠ C-True
    have conflicting S ≠ C-True using other'.hyps(1) c
      by (induct rule: cdclW-o-induct) auto
    then have conflict-is-false-with-level S'
      using cdclW-o-conflict-is-false-with-level-inv[OF other'.hyps(1)]
      other'.prems(3,5,6,2) by blast
    moreover have cdclW-cp** S' S'' using other'.hyps(3) unfolding full-def by auto
    then have S' = S'' using c
      by (induct rule: rtrancp-induct)
      (fastforce intro: conflicting-clause.exhaust)+
    ultimately have conflict-is-false-with-level S'' by auto
  }
  ultimately have conflict-is-false-with-level S'' by blast
}
moreover {
  assume confl: conflicting S' = C-True
  and D-L: ∀ D ∈ # clauses S'. trail S' ⊨as CNot D
    → (∃ L. L ∈ # D ∧ get-level L (trail S') = backtrack-lvl S')
  { assume ∀ D ∈ # clauses S'. ¬ trail S' ⊨as CNot D
    then have no-clause-is-false S' using ⟨conflicting S' = C-True⟩ by simp
    then have conflict-is-false-with-level S'' using calculation(3) by blast
  }
  moreover {
    assume ¬(∀ D ∈ # clauses S'. ¬ trail S' ⊨as CNot D)
    then obtain T D where
      propagate** S' T and
      conflict T S'' and
      D: D ∈ # clauses S' and
      trail S'' ⊨as CNot D and
      conflicting S'' = C-Clause D
    using full1-cdclW-cp-exists-conflict-full1-decompose[OF - - ⟨conflicting S' = C-True⟩]
    other'(3) by (metis (mono-tags, lifting) ball-msetI bex-msetI conflictE state-eq-trail
      trail-update-conflicting)
  }
}

```

obtain M **where** $M: \text{trail } S'' = M @ \text{trail } S'$ **and** $nm: \forall m \in \text{set } M. \neg \text{is-marked } m$
using $\text{rtrancpl-cdcl}_W\text{-cp-dropWhile-trail other' } (\beta)$ **unfolding** full-def **by** meson
have $\text{btS}: \text{backtrack-lvl } S'' = \text{backtrack-lvl } S'$
using $\text{other'.hyps}(\beta)$ **unfolding** full-def **by** $(\text{metis } \text{rtrancpl-cdcl}_W\text{-cp-backtrack-lvl})$
have $\text{inv}: \text{cdcl}_W\text{-M-level-inv } S''$
by $(\text{metis } (\text{no-types}) \text{cdcl}_W\text{-stgy.conflict' cdcl}_W\text{-stgy-consistent-inv full-unfold lev' other'.hyps}(\beta))$
then have $\text{nd}: \text{no-dup } (\text{trail } S'')$
by $(\text{metis } (\text{no-types}) \text{cdcl}_W\text{-M-level-inv-decomp}(2))$
have $\text{conflict-is-false-with-level } S''$
proof cases
assume $\text{trail } S' \models_{\text{as}} \text{CNot } D$
moreover then obtain L **where** $L \in \# D$ **and** $\text{get-level } L (\text{trail } S') = \text{backtrack-lvl } S'$
using $D\text{-L } D$ **by** blast
moreover
have $LS': -L \in \text{lits-of } (\text{trail } S')$
using $\langle \text{trail } S' \models_{\text{as}} \text{CNot } D \rangle \langle L \in \# D \rangle \text{in-CNot-implies-uminus}(2)$ **by** blast
{ fix $x :: ('v, \text{nat}, 'v \text{ literal multiset}) \text{ marked-lit}$ **and**
 $xb :: ('v, \text{nat}, 'v \text{ literal multiset}) \text{ marked-lit}$
assume $a1: x \in \text{set } (\text{trail } S')$ **and**
 $a2: xb \in \text{set } M$ **and**
 $a3: (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ ' set } M \cap (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ ' set } (\text{trail } S')$
 $= \{\}$ **and**
 $a4: -L = \text{lit-of } x$ **and**
 $a5: \text{atm-of } L = \text{atm-of } (\text{lit-of } xb)$
moreover have $\text{atm-of } (\text{lit-of } x) = \text{atm-of } L$
using $a4$ **by** $(\text{metis } (\text{no-types}) \text{atm-of-uminus})$
ultimately have False
using $a5 \ a3 \ a2 \ a1$ **by** auto
}
then have $\text{atm-of } L \notin \text{atm-of ' lits-of } M$
using $\text{nd } LS'$ **unfolding** M **by** $(\text{auto simp add: lits-of-def})$
then have $\text{get-level } L (\text{trail } S'') = \text{get-level } L (\text{trail } S')$
unfolding M **by** $(\text{simp add: lits-of-def})$
ultimately show $?thesis$ **using** $\text{btS } \langle \text{conflicting } S'' = \text{C-Clause } D \rangle$ **by** auto
next
assume $\neg \text{trail } S' \models_{\text{as}} \text{CNot } D$
then obtain L **where** $L \in \# D$ **and** $LM: -L \in \text{lits-of } M$
using $\langle \text{trail } S'' \models_{\text{as}} \text{CNot } D \rangle$
by $(\text{auto simp add: CNot-def true-clc-def } M \text{ true-annots-def true-annot-def split: split-if-asm})$
{ fix $x :: ('v, \text{nat}, 'v \text{ literal multiset}) \text{ marked-lit}$ **and**
 $xb :: ('v, \text{nat}, 'v \text{ literal multiset}) \text{ marked-lit}$
assume $a1: xb \in \text{set } (\text{trail } S')$ **and**
 $a2: x \in \text{set } M$ **and**
 $a3: \text{atm-of } L = \text{atm-of } (\text{lit-of } xb)$ **and**
 $a4: -L = \text{lit-of } x$ **and**
 $a5: (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ ' set } M \cap (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ ' set } (\text{trail } S')$
 $= \{\}$
moreover have $\text{atm-of } (\text{lit-of } xb) = \text{atm-of } (-L)$
using $a3$ **by** simp
ultimately have False
by auto **}**
then have $LS': \text{atm-of } L \notin \text{atm-of ' lits-of } (\text{trail } S')$
using $\text{nd } \langle L \in \# D \rangle LM$ **unfolding** M **by** $(\text{auto simp add: lits-of-def})$

```

show ?thesis
proof cases
  assume ne: get-all-levels-of-marked (trail S') = []
  have backtrack-lvl S'' = 0
    using inv ne nm unfolding cdclW-M-level-inv-def M
    by (simp add: get-all-levels-of-marked-nil-iff-not-is-marked)
  moreover
    have a1: get-rev-level L 0 (rev M) = 0
      using nm by auto
    then have get-level L (M @ trail S') = 0
      by (metis LS' get-all-levels-of-marked-nil-iff-not-is-marked
        get-level-skip-beginning-not-marked lits-of-def ne)
    ultimately show ?thesis using ⟨conflicting S'' = C-Clause D⟩ ⟨L ∈ # D⟩ unfolding M
      by auto
  next
    assume ne: get-all-levels-of-marked (trail S') ≠ []
    have hd (get-all-levels-of-marked (trail S')) = backtrack-lvl S'
      using ne lev' M nm unfolding cdclW-M-level-inv-def
      by (cases get-all-levels-of-marked (trail S'))
      (simp-all add: get-all-levels-of-marked-nil-iff-not-is-marked[symmetric])
    moreover have atm-of L ∈ atm-of ' lits-of M
      using ⟨¬L ∈ lits-of M⟩
      by (simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set lits-of-def)
    ultimately show ?thesis
      using nm ne ⟨L ∈ # D⟩ ⟨conflicting S'' = C-Clause D⟩
        get-level-skip-beginning-hd-get-all-levels-of-marked[OF LS', of M]
        get-level-skip-in-all-not-marked[of rev M L backtrack-lvl S']
      unfolding lits-of-def btS M
      by auto
    qed
  qed
}
ultimately have conflict-is-false-with-level S'' by blast
}
moreover
{
  assume conflicting S' ≠ C-True
  have no-clause-is-false S' using ⟨conflicting S' ≠ C-True⟩ by auto
  then have conflict-is-false-with-level S'' using calculation(3) by blast
}
ultimately show ?case by fast
qed

```

lemma rtrancp-cdcl_W-stgy-no-smaller-confl-inv:

assumes

cdcl_W-stgy** S S' **and**

n-l: no-smaller-confl S **and**

cls-false: conflict-is-false-with-level S **and**

lev: cdcl_W-M-level-inv S **and**

no-f: no-clause-is-false S **and**

dist: distinct-cdcl_W-state S **and**

conflicting: cdcl_W-conflicting S **and**

decomp: all-decomposition-implies-m (init-clss S) (get-all-marked-decomposition (trail S)) **and**

learned: cdcl_W-learned-clause S **and**

alien: no-strange-atm S

shows *no-smaller-confl* $S' \wedge$ *conflict-is-false-with-level* S'
using *assms*(1)
proof (*induct rule: rtranclp-induct*)
case *base*
then show ?*case* **using** *n-l cls-false* **by** *auto*
next
case (*step* $S' S''$) **note** $st = \text{this}(1)$ **and** $cdcl = \text{this}(2)$ **and** $IH = \text{this}(3)$
have *no-smaller-confl* S' **and** *conflict-is-false-with-level* S'
using IH **by** *blast+*
moreover have *cdcl_W-M-level-inv* S'
using st *lev rtranclp-cdcl_W-stgy-rtranclp-cdcl_W*
by (*blast intro: rtranclp-cdcl_W-consistent-inv*)+
moreover have *no-clause-is-false* S'
using st *no-f rtranclp-cdcl_W-stgy-not-non-negated-init-clss* **by** *blast*
moreover have *distinct-cdcl_W-state* S'
using *rtanclp-distinct-cdcl_W-state-inv*[*of* $S S'$] *lev rtranclp-cdcl_W-stgy-rtranclp-cdcl_W*[*OF* st]
dist **by** *auto*
moreover have *cdcl_W-conflicting* S'
using *rtranclp-cdcl_W-all-inv*(6)[*of* $S S'$] st *alien conflicting decomp dist learned lev*
rtranclp-cdcl_W-stgy-rtranclp-cdcl_W **by** *blast*
ultimately show ?*case*
using *cdcl_W-stgy-no-smaller-confl*[*OF* $cdcl$] *cdcl_W-stgy-ex-lit-of-max-level*[*OF* $cdcl$] **by** *fast*
qed

17.6.7 Final States are Conclusive

lemma *full-cdcl_W-stgy-final-state-conclusive-non-false*:
fixes $S' :: 'st$
assumes *full: full cdcl_W-stgy (init-state N) S'*
and *no-d: distinct-mset-mset N*
and *no-empty: $\forall D \in \#N. D \neq \{\#\}$*
shows (*conflicting* $S' = C\text{-Clause } \{\#\} \wedge$ *unsatisfiable (set-mset (init-clss S'))*)
 \vee (*conflicting* $S' = C\text{-True} \wedge$ *trail S' \models_{asm} init-clss S'*)
proof –
let ? $S = \text{init-state } N$
have
termi: $\forall S''. \neg \text{cdcl}_W\text{-stgy } S' S''$ and
step: $\text{cdcl}_W\text{-stgy}^ (\text{init-state } N) S'$ using full unfolding full-def by auto*
moreover have
learned: cdcl_W-learned-clause S' and
level-inv: cdcl_W-M-level-inv S' and
alien: no-strange-atm S' and
no-dup: distinct-cdcl_W-state S' and
confl: cdcl_W-conflicting S' and
decomp: all-decomposition-implies-m (init-clss S') (get-all-marked-decomposition (trail S'))
using *no-d tranclp-cdcl_W-stgy-tranclp-cdcl_W*[*of* ? $S S'$] *step rtranclp-cdcl_W-all-inv*(1–6)[*of* ? $S S'$]
unfolding *rtranclp-unfold* **by** *auto*
moreover
have $\forall D \in \#N. \neg \square \models_{as} C\text{Not } D$ **using** *no-empty* **by** *auto*
then have *confl-k: conflict-is-false-with-level S'*
using *rtranclp-cdcl_W-stgy-no-smaller-confl-inv*[*OF* *step*] *no-d* **by** *auto*
show ?*thesis*
using *cdcl_W-stgy-final-state-conclusive*[*OF* *termi decomp learned level-inv alien no-dup confl*
confl-k] .
qed

lemma *conflict-is-full1-cdcl_W-cp*:
 assumes *cp*: *conflict S S'*
 shows *full1 cdcl_W-cp S S'*
proof –
 have *cdcl_W-cp S S'* and *conflicting S' ≠ C-True* using *cp cdcl_W-cp.intros* by *auto*
 then have *cdcl_W-cp⁺⁺ S S'* by *blast*
 moreover have *no-step cdcl_W-cp S'*
 using *(conflicting S' ≠ C-True)* by (*metis cdcl_W-cp-conflicting-not-empty*
conflicting-clause.exhaust)
 ultimately show *full1 cdcl_W-cp S S'* unfolding *full1-def* by *blast+*
qed

lemma *cdcl_W-cp-fst-empty-conflicting-false*:
 assumes *cdcl_W-cp S S'*
 and *trail S = []*
 and *conflicting S ≠ C-True*
 shows *False*
 using *assms* by (*induct rule: cdcl_W-cp.induct*) *auto*

lemma *cdcl_W-o-fst-empty-conflicting-false*:
 assumes *cdcl_W-o S S'*
 and *trail S = []*
 and *conflicting S ≠ C-True*
 shows *False*
 using *assms* by (*induct rule: cdcl_W-o.induct*) *auto*

lemma *cdcl_W-stgy-fst-empty-conflicting-false*:
 assumes *cdcl_W-stgy S S'*
 and *trail S = []*
 and *conflicting S ≠ C-True*
 shows *False*
 using *assms* apply (*induct rule: cdcl_W-stgy.induct*)
 using *trancpD cdcl_W-cp-fst-empty-conflicting-false* unfolding *full1-def* apply *metis*
 using *cdcl_W-o-fst-empty-conflicting-false* by *blast*
thm *cdcl_W-cp.induct[split-format(complete)]*

lemma *cdcl_W-cp-conflicting-is-false*:
cdcl_W-cp S S' ⇒ conflicting S = C-Clause {#} ⇒ False
 by (*induction rule: cdcl_W-cp.induct*) *auto*

lemma *rtrancp-cdcl_W-cp-conflicting-is-false*:
cdcl_W-cp⁺⁺ S S' ⇒ conflicting S = C-Clause {#} ⇒ False
 apply (*induction rule: trancp.induct*)
 by (*auto dest: cdcl_W-cp-conflicting-is-false*)

lemma *cdcl_W-o-conflicting-is-false*:
cdcl_W-o S S' ⇒ conflicting S = C-Clause {#} ⇒ False
 by (*induction rule: cdcl_W-o.induct*) *auto*

lemma *cdcl_W-stgy-conflicting-is-false*:
cdcl_W-stgy S S' ⇒ conflicting S = C-Clause {#} ⇒ False
 apply (*induction rule: cdcl_W-stgy.induct*)
 unfolding *full1-def* apply (*metis (no-types) cdcl_W-cp-conflicting-not-empty trancpD*)

unfolding full-def by (*metis conflict-with-false-implies-terminated other*)

lemma *rtrancp-cdcl_W-stgy-conflicting-is-false:*
*cdcl_W-stgy** S S' \implies conflicting S = C-Clause {#} \implies S' = S*
apply (*induction rule: rtrancp-induct*)
apply *simp*
using *cdcl_W-stgy-conflicting-is-false by blast*

lemma *full-cdcl_W-init-clss-with-false-normal-form:*
assumes
 $\forall m \in \text{set } M. \neg \text{is-marked } m$ **and**
E = C-Clause D **and**
state S = (M, N, U, 0, E)
full cdcl_W-stgy S S' and
all-decomposition-implies-m (init-clss S) (get-all-marked-decomposition (trail S))
cdcl_W-learned-clause S
cdcl_W-M-level-inv S
no-strange-atm S
distinct-cdcl_W-state S
cdcl_W-conflicting S
shows $\exists M''. \text{state } S' = (M'', N, U, 0, \text{C-Clause } \{ \# \})$
using *assms(10,9,8,7,6,5,4,3,2,1)*
proof (*induction M arbitrary: E D S*)
case *Nil*
then show *?case*
using *rtrancp-cdcl_W-stgy-conflicting-is-false unfolding full-def cdcl_W-conflicting-def by auto*
next
case (*Cons L M*) **note** *IH = this(1) and full = this(8) and E = this(10) and inv = this(2-7) and*
S = this(9) and nm = this(11)
obtain *K p* **where** *K: L = Propagated K p*
using *nm by (cases L) auto*
have *every-mark-is-a-conflict S* **using** *inv unfolding cdcl_W-conflicting-def by auto*
then have *MpK: M \models_{as} CNot (p - {#K#}) and Kp: K $\in \#$ p*
using *S unfolding K by fastforce+*
then have *p: p = (p - {#K#}) + {#K#}*
by (*auto simp add: multiset-eq-iff*)
then have *K': L = Propagated K (((p - {#K#}) + {#K#}))*
using *K by auto*

consider (*D*) *D = {#} | (D') D \neq {#}* **by** *blast*
then show *?case*
proof *cases*
case *D*
then show *?thesis*
using *full rtrancp-cdcl_W-stgy-conflicting-is-false S unfolding full-def E D by auto*
next
case *D'*
then have *no-p: no-step propagate S and no-c: no-step conflict S*
using *S E by auto*
then have *no-step cdcl_W-cp S* **by** (*auto simp: cdcl_W-cp.simps*)
have *res-skip: $\exists T. (\text{resolve } S \ T \wedge \text{no-step skip } S \wedge \text{full cdcl_W-cp } T \ T)$*
 $\vee (\text{skip } S \ T \wedge \text{no-step resolve } S \wedge \text{full cdcl_W-cp } T \ T)$
proof *cases*
assume *-lit-of L $\notin \#$ D*
then obtain *T* **where** *sk: skip S T and res: no-step resolve S*

```

using  $S$  that  $D' K$  unfolding  $skip.simps E$  by  $fastforce$ 
have  $full\ cdcl_W\text{-}cp\ T\ T$ 
  using  $sk$  by ( $auto\ simp\ add: conflicting\text{-}clause\text{-}full\text{-}cdcl_W\text{-}cp$ )
then show  $?thesis$ 
  using  $sk\ res$  by  $blast$ 
next
assume  $LD: \neg\text{-}lit\text{-}of\ L \notin \# D$ 
then have  $D: C\text{-}Clause\ D = C\text{-}Clause\ ((D - \{\# \text{-} lit\text{-}of\ L\ \# \}) + \{\# \text{-} lit\text{-}of\ L\ \# \})$ 
  by ( $auto\ simp\ add: multiset\text{-}eq\text{-}iff$ )

have  $\bigwedge L. get\text{-}level\ L\ M = 0$ 
  by ( $simp\ add: nm$ )
then have  $get\text{-}maximum\text{-}level\ (D - \{\# \text{-} K\ \# \})$ 
  ( $Propagated\ K\ ((p - \{\# K\ \# \}) + \{\# K\ \# \}) \# M = 0$ )
  using  $LD\ get\text{-}maximum\text{-}level\text{-}exists\text{-}lit\text{-}of\text{-}max\text{-}level$ 
proof -
  obtain  $L'$  where  $get\text{-}level\ L' (L\ \# M) = get\text{-}maximum\text{-}level\ D (L\ \# M)$ 
    using  $LD\ get\text{-}maximum\text{-}level\text{-}exists\text{-}lit\text{-}of\text{-}max\text{-}level[of\ D\ L\ \# M]$  by  $fastforce$ 
  then show  $?thesis$  by ( $metis\ (mono\text{-}tags)\ K'\ bex\ msetE\ get\text{-}level\text{-}skip\text{-}all\text{-}not\text{-}marked$ 
     $get\text{-}maximum\text{-}level\text{-}exists\text{-}lit\ nm\ not\text{-}gr0$ )
  qed
then obtain  $T$  where  $sk: resolve\ S\ T$  and  $res: no\text{-}step\ skip\ S$ 
  using  $resolve\text{-}rule[of\ S\ K\ p - \{\# K\ \# \}\ M\ N\ U\ 0\ (D - \{\# \text{-} K\ \# \})$ 
     $update\text{-}conflicting\ (C\text{-}Clause\ (remdups\text{-}mset\ (D - \{\# \text{-} K\ \# \}) + (p - \{\# K\ \# \})))\ (tl\text{-}trail\ S)]$ 
     $S$  unfolding  $K'\ D\ E$  by  $fastforce$ 
have  $full\ cdcl_W\text{-}cp\ T\ T$ 
  using  $sk$  by ( $auto\ simp\ add: conflicting\text{-}clause\text{-}full\text{-}cdcl_W\text{-}cp$ )
then show  $?thesis$ 
  using  $sk\ res$  by  $blast$ 
qed
then have  $step\text{-}s: \exists T. cdcl_W\text{-}stgy\ S\ T$ 
  using ( $no\text{-}step\ cdcl_W\text{-}cp\ S$ )  $other'$  by ( $meson\ bj\ resolve\ skip$ )
have  $get\text{-}all\text{-}marked\text{-}decomposition\ (L\ \# M) = [([], L\ \# M)]$ 
  using  $nm$  unfolding  $K$  apply ( $induction\ M\ rule: marked\text{-}lit\text{-}list\text{-}induct, simp$ )
  by ( $case\text{-}tac\ hd\ (get\text{-}all\text{-}marked\text{-}decomposition\ xs), auto$ ) +
then have  $no\text{-}b: no\text{-}step\ backtrack\ S$ 
  using  $nm\ S$  by  $auto$ 
have  $no\text{-}d: no\text{-}step\ decide\ S$ 
  using  $S\ E$  by  $auto$ 

have  $full\text{-}S\text{-}S: full\ cdcl_W\text{-}cp\ S\ S$ 
  using  $S\ E$  by ( $auto\ simp\ add: conflicting\text{-}clause\text{-}full\text{-}cdcl_W\text{-}cp$ )
then have  $no\text{-}f: no\text{-}step\ (full1\ cdcl_W\text{-}cp)\ S$ 
  unfolding  $full\text{-}def\ full1\text{-}def\ rtranclp\text{-}unfold$  by ( $meson\ tranclpD$ )
obtain  $T$  where
   $s: cdcl_W\text{-}stgy\ S\ T$  and  $st: cdcl_W\text{-}stgy^{**}\ T\ S'$ 
  using  $full\ step\text{-}s\ full$  unfolding  $full\text{-}def$  by ( $metis\ rtranclp\text{-}unfold\ tranclpD$ )
have  $resolve\ S\ T \vee skip\ S\ T$ 
  using  $s\ no\text{-}b\ no\text{-}d\ res\ skip\ full\text{-}S\text{-}S$  unfolding  $cdcl_W\text{-}stgy.simps\ cdcl_W\text{-}o.simps\ full\text{-}unfold$ 
     $full1\text{-}def$ 
  by ( $auto\ dest!: tranclpD\ simp: cdcl_W\text{-}bj.simps$ )
then obtain  $D'$  where  $T: state\ T = (M, N, U, 0, C\text{-}Clause\ D')$ 
  using  $S\ E$  by  $auto$ 

have  $st\text{-}c: cdcl_W^{**}\ S\ T$ 

```

```

    using E T rtrancpl-cdclW-stgy-rtrancpl-cdclW s by blast
have cdclW-conflicting T
    using rtrancpl-cdclW-all-inv(6)[OF st-c inv(6,5,4,3,2,1)] .
show ?thesis
    apply (rule IH[of T])
        using rtrancpl-cdclW-all-inv(6)[OF st-c inv(6,5,4,3,2,1)] apply blast
        using rtrancpl-cdclW-all-inv(5)[OF st-c inv(6,5,4,3,2,1)] apply blast
        using rtrancpl-cdclW-all-inv(4)[OF st-c inv(6,5,4,3,2,1)] apply blast
        using rtrancpl-cdclW-all-inv(3)[OF st-c inv(6,5,4,3,2,1)] apply blast
        using rtrancpl-cdclW-all-inv(2)[OF st-c inv(6,5,4,3,2,1)] apply blast
        using rtrancpl-cdclW-all-inv(1)[OF st-c inv(6,5,4,3,2,1)] apply blast
    apply (metis full-def st full)
    using T E apply blast
    apply auto[]
    using nm by simp
qed
qed

lemma full-cdclW-stgy-final-state-conclusive-is-one-false:
  fixes S' :: 'st
  assumes full: full cdclW-stgy (init-state N) S'
  and no-d: distinct-mset-mset N
  and empty: {#} ∈ # N
  shows conflicting S' = C-Clause {#} ∧ unsatisfiable (set-mset (init-clss S'))
proof -
  let ?S = init-state N
  have cdclW-stgy** ?S S' and no-step cdclW-stgy S' using full unfolding full-def by auto
  then have plus-or-eq: cdclW-stgy++ ?S S' ∨ S' = ?S unfolding rtrancpl-unfold by auto
  have ∃ S''. conflict ?S S'' using empty not-conflict-not-any-negated-init-clss by force

  then have cdclW-stgy: ∃ S'. cdclW-stgy ?S S'
    using cdclW-cp.conflict'[of ?S] conflict-is-full1-cdclW-cp cdclW-stgy.intros(1) by metis
  have S' ≠ ?S using (no-step cdclW-stgy S') cdclW-stgy by blast

  then obtain St:: 'st where St: cdclW-stgy ?S St and cdclW-stgy** St S'
    using plus-or-eq by (metis (no-types) (cdclW-stgy** ?S S') converse-rtrancplE)
  have st: cdclW** ?S St
    by (simp add: rtrancpl-unfold (cdclW-stgy ?S St) cdclW-stgy-trancpl-cdclW)

  have ∃ T. conflict ?S T
    using empty not-conflict-not-any-negated-init-clss by force
  then have fullSt: full1 cdclW-cp ?S St
    using St unfolding cdclW-stgy.simps by blast
  then have bt: backtrack-lvl St = (0::nat)
    using rtrancpl-cdclW-cp-backtrack-lvl unfolding full1-def
    by (fastforce dest!: trancpl-into-rtrancpl)
  have cls-St: init-clss St = N
    using fullSt cdclW-stgy-no-more-init-clss[OF St] by auto
  have conflicting St ≠ C-True
  proof (rule ccontr)
    assume ¬ ?thesis
    then have ∃ T. conflict St T
      using empty cls-St by (fastforce simp: clauses-def)
    then show False using fullSt unfolding full1-def by blast
  qed
qed

```

have 1: $\forall m \in \text{set } (\text{trail } St). \neg \text{is-marked } m$
using *fullSt unfolding full1-def* **by** (*auto dest!*: *rtranclp-into-rtranclp*
rtranclp-cdcl_W-cp-dropWhile-trail)
have 2: *full cdcl_W-stgy St S'*
using $\langle \text{cdcl}_W\text{-stgy}^{**} St S' \rangle \langle \text{no-step cdcl}_W\text{-stgy } S' \rangle$ **bt** *unfolding full-def* **by** *auto*
have 3: *all-decomposition-implies-m*
(init-clss St)
(get-all-marked-decomposition
(trail St))
using *rtranclp-cdcl_W-all-inv(1)[OF st] no-d* **bt** **by** *simp*
have 4: *cdcl_W-learned-clause St*
using *rtranclp-cdcl_W-all-inv(2)[OF st] no-d* **bt** **by** *simp*
have 5: *cdcl_W-M-level-inv St*
using *rtranclp-cdcl_W-all-inv(3)[OF st] no-d* **bt** **by** *simp*
have 6: *no-strange-atm St*
using *rtranclp-cdcl_W-all-inv(4)[OF st] no-d* **bt** **by** *simp*
have 7: *distinct-cdcl_W-state St*
using *rtranclp-cdcl_W-all-inv(5)[OF st] no-d* **bt** **by** *simp*
have 8: *cdcl_W-conflicting St*
using *rtranclp-cdcl_W-all-inv(6)[OF st] no-d* **bt** **by** *simp*
have *init-clss S' = init-clss St* **and** *conflicting S' = C-Clause {#}*
using $\langle \text{conflicting } St \neq C\text{-True} \rangle$ *full-cdcl_W-init-clss-with-false-normal-form[OF 1, of - - St]*
2 3 4 5 6 7 8 St **apply** (*metis* $\langle \text{cdcl}_W\text{-stgy}^{**} St S' \rangle$ *rtranclp-cdcl_W-stgy-no-more-init-clss*)
using $\langle \text{conflicting } St \neq C\text{-True} \rangle$ *full-cdcl_W-init-clss-with-false-normal-form[OF 1, of - - St - -*
S'] 2 3 4 5 6 7 8 **by** (*metis* *bt conflicting-clause.exhaust prod.inject*)

moreover **have** *init-clss S' = N*
using $\langle \text{cdcl}_W\text{-stgy}^{**} (\text{init-state } N) S' \rangle$ *rtranclp-cdcl_W-stgy-no-more-init-clss* **by** *fastforce*
moreover **have** *unsatisfiable (set-mset N)*
by (*meson empty mem-set-mset-iff satisfiable-def true-clss-empty true-clss-def*)
ultimately **show** *?thesis* **by** *auto*
qed

lemma *full-cdcl_W-stgy-final-state-conclusive:*

fixes *S' :: 'st*
assumes *full: full cdcl_W-stgy (init-state N) S'* **and** *no-d: distinct-mset-mset N*
shows $(\text{conflicting } S' = C\text{-Clause } \{ \# \} \wedge \text{unsatisfiable } (\text{set-mset } (\text{init-clss } S')))$
 $\vee (\text{conflicting } S' = C\text{-True} \wedge \text{trail } S' \models_{\text{asm}} \text{init-clss } S')$
using *assms full-cdcl_W-stgy-final-state-conclusive-is-one-false*
full-cdcl_W-stgy-final-state-conclusive-non-false **by** *blast*

lemma *full-cdcl_W-stgy-final-state-conclusive-from-init-state:*

fixes *S' :: 'st*
assumes *full: full cdcl_W-stgy (init-state N) S'*
and *no-d: distinct-mset-mset N*
shows $(\text{conflicting } S' = C\text{-Clause } \{ \# \} \wedge \text{unsatisfiable } (\text{set-mset } N))$
 $\vee (\text{conflicting } S' = C\text{-True} \wedge \text{trail } S' \models_{\text{asm}} N \wedge \text{satisfiable } (\text{set-mset } N))$

proof –

have *N: init-clss S' = N*
using *full unfolding full-def* **by** (*auto dest: rtranclp-cdcl_W-stgy-no-more-init-clss*)
consider
 (confl) *conflicting S' = C-Clause {#}* **and** *unsatisfiable (set-mset (init-clss S'))*
 $|$ (sat) *conflicting S' = C-True* **and** *trail S' \models_{asm} init-clss S'*

```

    using full-cdclW-stgy-final-state-conclusive[OF assms] by auto
  then show ?thesis
  proof cases
    case confl
    then show ?thesis by (auto simp: N)
  next
    case sat
    have cdclW-M-level-inv (init-state N) by auto
    then have cdclW-M-level-inv S'
      using full rtrancp-cdclW-stgy-consistent-inv unfolding full-def by blast
    then have consistent-interp (lits-of (trail S')) unfolding cdclW-M-level-inv-def by blast
    moreover have lits-of (trail S')  $\models_s$  set-mset (init-clss S')
      using sat(2) by (auto simp add: true-annots-def true-annot-def true-clss-def)
    ultimately have satisfiable (set-mset (init-clss S')) by simp
    then show ?thesis using sat unfolding N by blast
  qed
qed
end
end
theory CDCL-W-Termination
imports CDCL-W
begin

context cdclW-ops
begin

```

17.7 Termination

The condition that no learned clause is a tautology is overkill (in the sense that the no-duplicate condition is enough), but we can reuse *build-all-simple-clss*.

The invariant contains all the structural invariants that holds,

definition *cdcl_W-all-struct-inv* where

```

cdclW-all-struct-inv S =
  (no-strange-atm S  $\wedge$  cdclW-M-level-inv S
   $\wedge$  ( $\forall s \in \#$  learned-clss S.  $\neg$ tautology s)
   $\wedge$  distinct-cdclW-state S  $\wedge$  cdclW-conflicting S
   $\wedge$  all-decomposition-implies-m (init-clss S) (get-all-marked-decomposition (trail S))
   $\wedge$  cdclW-learned-clause S)

```

lemma *cdcl_W-all-struct-inv-inv*:

```

assumes cdclW S S' and cdclW-all-struct-inv S
shows cdclW-all-struct-inv S'
unfolding cdclW-all-struct-inv-def
proof (intro HOL.conjI)
  show no-strange-atm S'
    using cdclW-all-inv[OF assms(1)] assms(2) unfolding cdclW-all-struct-inv-def by auto
  show cdclW-M-level-inv S'
    using cdclW-all-inv[OF assms(1)] assms(2) unfolding cdclW-all-struct-inv-def by fast
  show distinct-cdclW-state S'
    using cdclW-all-inv[OF assms(1)] assms(2) unfolding cdclW-all-struct-inv-def by fast
  show cdclW-conflicting S'
    using cdclW-all-inv[OF assms(1)] assms(2) unfolding cdclW-all-struct-inv-def by fast
  show all-decomposition-implies-m (init-clss S') (get-all-marked-decomposition (trail S'))
    using cdclW-all-inv[OF assms(1)] assms(2) unfolding cdclW-all-struct-inv-def by fast
  show cdclW-learned-clause S'

```

```

using  $cdcl_W$ -all-inv[ $OF$   $assms(1)$ ]  $assms(2)$  unfolding  $cdcl_W$ -all-struct-inv-def by fast

show  $\forall s \in \#learned-clss\ S'. \neg \text{tautology } s$ 
  using  $assms(1)$ [ $THEN$   $learned-clss\ are\ not\ tautologies$ ]  $assms(2)$ 
  unfolding  $cdcl_W$ -all-struct-inv-def by fast
qed

```

```

lemma  $rtranclp$ - $cdcl_W$ -all-struct-inv-inv:
  assumes  $cdcl_W^{**}\ S\ S'$  and  $cdcl_W$ -all-struct-inv  $S$ 
  shows  $cdcl_W$ -all-struct-inv  $S'$ 
  using  $assms$  by induction (auto intro:  $cdcl_W$ -all-struct-inv-inv)

```

```

lemma  $cdcl_W$ -stgy- $cdcl_W$ -all-struct-inv:
   $cdcl_W$ -stgy  $S\ T \implies cdcl_W$ -all-struct-inv  $S \implies cdcl_W$ -all-struct-inv  $T$ 
  by (meson  $cdcl_W$ -stgy- $rtranclp$ - $cdcl_W$   $rtranclp$ - $cdcl_W$ -all-struct-inv-inv  $rtranclp$ -unfold)

```

```

lemma  $rtranclp$ - $cdcl_W$ -stgy- $cdcl_W$ -all-struct-inv:
   $cdcl_W$ -stgy $^{**}\ S\ T \implies cdcl_W$ -all-struct-inv  $S \implies cdcl_W$ -all-struct-inv  $T$ 
  by (induction rule:  $rtranclp$ -induct) (auto intro:  $cdcl_W$ -stgy- $cdcl_W$ -all-struct-inv)

```

17.8 No Relearning of a clause

```

lemma  $cdcl_W$ -o-new-clause-learned-is-backtrack-step:
  assumes  $learned: D \in \#learned-clss\ T$  and
   $new: D \notin \#learned-clss\ S$  and
   $cdcl_W: cdcl_W-o\ S\ T$  and
   $lev: cdcl_W$ - $M$ -level-inv  $S$ 
  shows  $backtrack\ S\ T \wedge conflicting\ S = C\text{-Clause}\ D$ 
  using  $cdcl_W$   $lev$   $learned$   $new$ 
proof (induction rule:  $cdcl_W$ -o-induct-lev2)
  case ( $backtrack\ K\ i\ M1\ M2\ L\ C\ T$ ) note  $decomp = this(1)$  and  $undef = this(6)$  and  $T = this(7)$ 
and
   $D-T = this(9)$  and  $D-S = this(10)$ 
  then have  $D = C + \{\#L\# \}$ 
  using  $not-gr0\ lev$  by (auto simp:  $cdcl_W$ - $M$ -level-inv-decomp if-0-1-ge-0)
  then show ?case
  using  $T$   $backtrack.hyps(1-5)$   $backtrack.intros$  by auto
qed auto

```

```

lemma  $cdcl_W$ -cp-new-clause-learned-has-backtrack-step:
  assumes  $learned: D \in \#learned-clss\ T$  and
   $new: D \notin \#learned-clss\ S$  and
   $cdcl_W: cdcl_W$ -stgy  $S\ T$  and
   $lev: cdcl_W$ - $M$ -level-inv  $S$ 
  shows  $\exists S'. backtrack\ S\ S' \wedge cdcl_W$ -stgy $^{**}\ S'\ T \wedge conflicting\ S = C\text{-Clause}\ D$ 
  using  $cdcl_W$   $learned$   $new$ 
proof (induction rule:  $cdcl_W$ -stgy.induct)
  case ( $conflict'\ S'$ )
  then show ?case
  unfolding full1-def by (metis (mono-tags, lifting)  $rtranclp$ - $cdcl_W$ -cp-learned-clause-inv
     $tranclp$ -into- $rtranclp$ )
next
  case ( $other'\ S'\ S''$ )
  then have  $D \in \#learned-clss\ S'$ 
  unfolding full-def by (auto dest:  $rtranclp$ - $cdcl_W$ -cp-learned-clause-inv)
  then show ?case

```

using *cdcl_W-o-new-clause-learned-is-backtrack-step*[*OF* - $\langle D \notin \# \text{ learned-clss } S \rangle \langle \text{cdcl}_W\text{-o } S \ S' \rangle$]
 $\langle \text{full cdcl}_W\text{-cp } S' \ S'' \rangle \text{ lev}$ **by** (*metis cdcl_W-stgy.conflict'* *full-unfold r-into-rtrancpl*
rtrancpl.rtrancpl-refl)
qed

lemma *rtrancpl-cdcl_W-cp-new-clause-learned-has-backtrack-step*:
assumes *learned*: $D \in \# \text{ learned-clss } T$ **and**
new: $D \notin \# \text{ learned-clss } S$ **and**
cdcl_W: *cdcl_W-stgy*** $S \ T$ **and**
lev: *cdcl_W-M-level-inv* S
shows $\exists S' \ S''. \text{cdcl}_W\text{-stgy}^{**} \ S \ S' \wedge \text{backtrack } S' \ S'' \wedge \text{conflicting } S' = C\text{-Clause } D \wedge$
 $\text{cdcl}_W\text{-stgy}^{**} \ S'' \ T$
using *cdcl_W learned new*
proof (*induction rule: rtrancpl-induct*)
case *base*
then show ?*case* **by** *blast*
next
case (*step* $T \ U$) **note** *st* = *this*(1) **and** *o* = *this*(2) **and** *IH* = *this*(3) **and**
 $D \cdot U = \text{this}(4)$ **and** $D \cdot S = \text{this}(5)$
show ?*case*
proof (*cases* $D \in \# \text{ learned-clss } T$)
case *True*
then obtain $S' \ S''$ **where**
st': *cdcl_W-stgy*** $S \ S'$ **and**
bt: *backtrack* $S' \ S''$ **and**
confl: *conflicting* $S' = C\text{-Clause } D$ **and**
st'': *cdcl_W-stgy*** $S'' \ T$
using *IH D-S* **by** *metis*
then show ?*thesis* **using** *o* **by** (*meson rtrancpl.simps*)
next
case *False*
have *cdcl_W-M-level-inv* T
using *lev rtrancpl-cdcl_W-stgy-consistent-inv st* **by** *blast*
then obtain S' **where**
bt: *backtrack* $T \ S'$ **and**
st': *cdcl_W-stgy*** $S' \ U$ **and**
confl: *conflicting* $T = C\text{-Clause } D$
using *cdcl_W-cp-new-clause-learned-has-backtrack-step*[*OF* $D \cdot U \ \text{False} \ o$]
by *metis*
then have *cdcl_W-stgy*** $S \ T$ **and**
backtrack $T \ S'$ **and**
conflicting $T = C\text{-Clause } D$ **and**
*cdcl_W-stgy*** $S' \ U$
using *o st* **by** *auto*
then show ?*thesis* **by** *blast*
qed
qed

lemma *propagate-no-more-Marked-lit*:
assumes *propagate* $S \ S'$
shows $\text{Marked } K \ i \in \text{set } (\text{trail } S) \longleftrightarrow \text{Marked } K \ i \in \text{set } (\text{trail } S')$
using *assms* **by** *auto*

lemma *conflict-no-more-Marked-lit*:
assumes *conflict* $S \ S'$

shows $\text{Marked } K \ i \in \text{set } (\text{trail } S) \longleftrightarrow \text{Marked } K \ i \in \text{set } (\text{trail } S')$
using *assms* **by** *auto*

lemma *cdcl_W-cp-no-more-Marked-lit*:
assumes *cdcl_W-cp* *S S'*
shows $\text{Marked } K \ i \in \text{set } (\text{trail } S) \longleftrightarrow \text{Marked } K \ i \in \text{set } (\text{trail } S')$
using *assms* **apply** (*induct rule: cdcl_W-cp.induct*)
using *conflict-no-more-Marked-lit propagate-no-more-Marked-lit* **by** *auto*

lemma *rtrancpl-cdcl_W-cp-no-more-Marked-lit*:
assumes *cdcl_W-cp*** *S S'*
shows $\text{Marked } K \ i \in \text{set } (\text{trail } S) \longleftrightarrow \text{Marked } K \ i \in \text{set } (\text{trail } S')$
using *assms* **apply** (*induct rule: rtrancpl-induct*)
using *cdcl_W-cp-no-more-Marked-lit* **by** *blast+*

lemma *cdcl_W-o-no-more-Marked-lit*:
assumes *cdcl_W-o* *S S'* **and** *cdcl_W-M-level-inv* *S* **and** $\neg \text{decide } S \ S'$
shows $\text{Marked } K \ i \in \text{set } (\text{trail } S') \longrightarrow \text{Marked } K \ i \in \text{set } (\text{trail } S)$
using *assms*
proof (*induct rule: cdcl_W-o-induct-lev2*)
case *backtrack* **note** *decomp = this(1)* **and** *undef = this(6)* **and** *T = this(7)* **and** *lev = this(8)*
then show *?case*
by (*auto simp: cdcl_W-M-level-inv-decomp*)
next
case (*decide L T*)
then show *?case* **by** *blast*
qed *auto*

lemma *cdcl_W-new-marked-at-beginning-is-decide*:
assumes *cdcl_W-stgy* *S S'* **and**
lev: cdcl_W-M-level-inv *S* **and**
trail S' = M' @ Marked L i # M **and**
trail S = M
shows $\exists T. \text{decide } S \ T \wedge \text{no-step } \text{cdcl}_W\text{-cp } S$
using *assms*
proof (*induct rule: cdcl_W-stgy.induct*)
case (*conflict' S'*) **note** *st = this(1)* **and** *no-dup = this(2)* **and** *S' = this(3)* **and** *S = this(4)*
have *cdcl_W-M-level-inv* *S'*
using *full1-cdcl_W-cp-consistent-inv no-dup st* **by** *blast*
then have $\text{Marked } L \ i \in \text{set } (\text{trail } S') \text{ and } \text{Marked } L \ i \notin \text{set } (\text{trail } S)$
using *no-dup unfolding S S' cdcl_W-M-level-inv-def* **by** (*auto simp add: rev-image-eqI*)
then have *False*
using *st rtrancpl-cdcl_W-cp-no-more-Marked-lit[of S S']*
unfolding *full1-def rtrancpl-unfold* **by** *blast*
then show *?case* **by** *fast*
next
case (*other' T U*) **note** *o = this(1)* **and** *ns = this(2)* **and** *st = this(3)* **and** *no-dup = this(4)* **and**
S' = this(5) **and** *S = this(6)*
have *cdcl_W-M-level-inv* *U*
by (*metis (full-types) lev cdcl_W.simps cdcl_W-consistent-inv full-def o*
other'.hyps(3) rtrancpl-cdcl_W-cp-consistent-inv)
then have $\text{Marked } L \ i \in \text{set } (\text{trail } U) \text{ and } \text{Marked } L \ i \notin \text{set } (\text{trail } S)$
using *no-dup unfolding S S' cdcl_W-M-level-inv-def* **by** (*auto simp add: rev-image-eqI*)
then have $\text{Marked } L \ i \in \text{set } (\text{trail } T)$
using *st rtrancpl-cdcl_W-cp-no-more-Marked-lit* **unfolding** *full-def* **by** *blast*

then show *?case*
using *cdcl_W-o-no-more-Marked-lit[OF o] ⟨Marked L i ∉ set (trail S)⟩ ns lev* **by** *meson*
qed

lemma *cdcl_W-o-is-decide*:

assumes *cdcl_W-o S' T and cdcl_W-M-level-inv S'*
trail T = drop (length M₀) M' @ Marked L i # H @ M **and**
 $\neg (\exists M'. \text{trail } S' = M' @ \text{Marked } L \ i \ \# \ H @ M)$
shows *decide S' T*

using *assms*

proof (*induction rule:cdcl_W-o-induct-lev2*)

case (*backtrack K i M1 M2 L D*)

then obtain *c* **where** *trail S' = c @ M2 @ Marked K (Suc i) # M1*

by *auto*

then show *?case*

using *backtrack by (cases drop (length M₀) M') (auto simp: cdcl_W-M-level-inv-def)*

next

case *decide*

show *?case* **using** *decide-rule[of S'] decide(1-4)* **by** *auto*

qed *auto*

lemma *rtrancpl-cdcl_W-new-marked-at-beginning-is-decide*:

assumes *cdcl_W-stgy** R U and*

trail U = M' @ Marked L i # H @ M **and**

trail R = M **and**

cdcl_W-M-level-inv R

shows

$\exists S \ T \ T'. \text{cdcl}_W\text{-stgy}^{**} \ R \ S \wedge \text{decide } S \ T \wedge \text{cdcl}_W\text{-stgy}^{**} \ T \ U \wedge \text{cdcl}_W\text{-stgy}^{**} \ S \ U \wedge$
 $\text{no-step } \text{cdcl}_W\text{-cp } S \wedge \text{trail } T = \text{Marked } L \ i \ \# \ H @ M \wedge \text{trail } S = H @ M \wedge \text{cdcl}_W\text{-stgy } S \ T' \wedge$
 $\text{cdcl}_W\text{-stgy}^{**} \ T' \ U$

using *assms*

proof (*induct arbitrary: M H M' i rule: rtrancpl-induct*)

case *base*

then show *?case* **by** *auto*

next

case (*step T U*) **note** *st = this(1)* **and** *IH = this(3)* **and** *s = this(2)* **and**

U = this(4) **and** *S = this(5)* **and** *lev = this(6)*

show *?case*

proof (*cases $\exists M'. \text{trail } T = M' @ \text{Marked } L \ i \ \# \ H @ M$*)

case *False*

with *s* **show** *?thesis* **using** *U s st S*

proof *induction*

case (*conflict' W*) **note** *cp = this(1)* **and** *nd = this(2)* **and** *W = this(3)*

then obtain *M₀* **where** *trail W = M₀ @ trail T* **and** *nmarked: $\forall l \in \text{set } M_0. \neg \text{is-marked } l$*

using *rtrancpl-cdcl_W-cp-dropWhile-trail unfolding full1-def rtrancpl-unfold* **by** *meson*

then have *MV: $M' @ \text{Marked } L \ i \ \# \ H @ M = M_0 @ \text{trail } T$* **unfolding** *W* **by** *simp*

then have *V: $\text{trail } T = \text{drop } (\text{length } M_0) (M' @ \text{Marked } L \ i \ \# \ H @ M)$*

by *auto*

have *takeWhile (Not o is-marked) M' = M₀ @ takeWhile (Not o is-marked) (trail T)*

using *arg-cong[OF MV, of takeWhile (Not o is-marked)] nmarked*

by (*simp add: takeWhile-tail*)

from *arg-cong[OF this, of length]* **have** *length M₀ ≤ length M'*

unfolding *length-append* **by** (*metis (no-types, lifting) Nat.le-trans le-add1 length-takeWhile-le*)

then have *False* **using** *nd V* **by** *auto*

```

then show ?case by fast
next
case (other' T' U) note o = this(1) and ns = this(2) and cp = this(3) and nd = this(4)
  and U = this(5) and st = this(6)
obtain M0 where trail U = M0 @ trail T' and nmarked:  $\forall l \in \text{set } M_0. \neg \text{is-marked } l$ 
  using rtrancp-cdclW-cp-dropWhile-trail cp unfolding full-def by meson
then have MV: M' @ Marked L i # H @ M = M0 @ trail T' unfolding U by simp
then have V: trail T' = drop (length M0) (M' @ Marked L i # H @ M)
  by auto
have takeWhile (Not o is-marked) M' = M0 @ takeWhile (Not o is-marked) (trail T')
  using arg-cong[OF MV, of takeWhile (Not o is-marked)] nmarked
  by (simp add: takeWhile-tail)
from arg-cong[OF this, of length] have length M0 ≤ length M'
  unfolding length-append by (metis (no-types, lifting) Nat.le-trans le-add1
    length-takeWhile-le)
then have tr-T': trail T' = drop (length M0) M' @ Marked L i # H @ M using V by auto
then have LT': Marked L i ∈ set (trail T') by auto
moreover
  have cdclW-M-level-inv T
    using lev rtrancp-cdclW-stgy-consistent-inv step.hyps(1) by blast
  then have decide T T' using o nd tr-T' cdclW-o-is-decide by metis
ultimately have decide T T' using cdclW-o-no-more-Marked-lit[OF o] by blast
then have 1: cdclW-stgy** R T and 2: decide T T' and 3: cdclW-stgy** T' U
  using st other'.prems(4)
  by (metis cdclW-stgy.conflict' cp full-unfold r-into-rtrancp rtrancp.rtrancp-refl)+
have [simp]: drop (length M0) M' = []
  using ⟨decide T T'⟩ ⟨Marked L i ∈ set (trail T')⟩ nd tr-T'
  by (auto simp add: Cons-eq-append-conv)
have T': drop (length M0) M' @ Marked L i # H @ M = Marked L i # trail T
  using ⟨decide T T'⟩ ⟨Marked L i ∈ set (trail T')⟩ nd tr-T'
  by auto
have trail T' = Marked L i # trail T
  using ⟨decide T T'⟩ ⟨Marked L i ∈ set (trail T')⟩ tr-T'
  by auto
then have 5: trail T' = Marked L i # H @ M
  using append.simps(1) list.sel(3) local.other'(5) tl-append2 by (simp add: tr-T')
have 6: trail T = H @ M
  by (metis (no-types) ⟨trail T' = Marked L i # trail T⟩
    ⟨trail T' = drop (length M0) M' @ Marked L i # H @ M⟩ append-Nil list.sel(3) nd
    tl-append2)
have 7: cdclW-stgy** T U using other'.prems(4) st by auto
have 8: cdclW-stgy T U cdclW-stgy** U U
  using cdclW-stgy.other'[OF other'(1-3)] by simp-all
show ?case apply (rule exI[of - T], rule exI[of - T'], rule exI[of - U])
  using ns 1 2 3 5 6 7 8 by fast
qed
next
case True
then obtain M' where T: trail T = M' @ Marked L i # H @ M by metis
from IH[OF this S lev] obtain S' S'' S''' where
  1: cdclW-stgy** R S' and
  2: decide S' S'' and
  3: cdclW-stgy** S'' T and
  4: no-step cdclW-cp S' and
  6: trail S'' = Marked L i # H @ M and

```

7: $\text{trail } S' = H @ M$ and
 8: $\text{cdcl}_W\text{-stgy}^{**} S' T$ and
 9: $\text{cdcl}_W\text{-stgy } S' S'''$ and
 10: $\text{cdcl}_W\text{-stgy}^{**} S''' T$
 by *blast*
 have $\text{cdcl}_W\text{-stgy}^{**} S'' U$ using $s \langle \text{cdcl}_W\text{-stgy}^{**} S'' T \rangle$ by *auto*
 moreover have $\text{cdcl}_W\text{-stgy}^{**} S' U$ using $8 s$ by *auto*
 moreover have $\text{cdcl}_W\text{-stgy}^{**} S''' U$ using $10 s$ by *auto*
 ultimately show *?thesis* apply – apply (rule $\text{exI[of - } S']$, rule $\text{exI[of - } S']$)
 using $1\ 2\ 4\ 6\ 7\ 8\ 9$ by *blast*
 qed
 qed

lemma *rtrancp-cdcl_W-new-marked-at-beginning-is-decide'*:
 assumes $\text{cdcl}_W\text{-stgy}^{**} R U$ and
 trail $U = M' @ \text{Marked } L\ i \# H @ M$ and
 trail $R = M$ and
 $\text{cdcl}_W\text{-M-level-inv } R$
 shows $\exists y\ y'. \text{cdcl}_W\text{-stgy}^{**} R y \wedge \text{cdcl}_W\text{-stgy } y\ y' \wedge \neg (\exists c. \text{trail } y = c @ \text{Marked } L\ i \# H @ M)$
 $\wedge (\lambda a\ b. \text{cdcl}_W\text{-stgy } a\ b \wedge (\exists c. \text{trail } a = c @ \text{Marked } L\ i \# H @ M))^{**} y' U$
proof –
 fix T'
 obtain $S' T T'$ where
 st: $\text{cdcl}_W\text{-stgy}^{**} R S'$ and
 decide $S' T$ and
 TU: $\text{cdcl}_W\text{-stgy}^{**} T U$ and
 no-step $\text{cdcl}_W\text{-cp } S'$ and
 trT: trail $T = \text{Marked } L\ i \# H @ M$ and
 trS': trail $S' = H @ M$ and
 S'U: $\text{cdcl}_W\text{-stgy}^{**} S' U$ and
 S'T': $\text{cdcl}_W\text{-stgy } S' T'$ and
 T'U: $\text{cdcl}_W\text{-stgy}^{**} T' U$
 using *rtrancp-cdcl_W-new-marked-at-beginning-is-decide[OF assms]* by *blast*
 have $n: \neg (\exists c. \text{trail } S' = c @ \text{Marked } L\ i \# H @ M)$ using *trS'* by *auto*
 show *?thesis*
 using *rtrancp-trans[OF st]* *rtrancp-exists-last-with-prop[of cdcl_W-stgy S' T' -*
 $\lambda a\ -. \neg (\exists c. \text{trail } a = c @ \text{Marked } L\ i \# H @ M), \text{OF } S'T' T'U n]$
 by *meson*
 qed

lemma *beginning-not-marked-invert*:
 assumes $A: M @ A = M' @ \text{Marked } K\ i \# H$ and
 nm: $\forall m \in \text{set } M. \neg \text{is-marked } m$
 shows $\exists M. A = M @ \text{Marked } K\ i \# H$
proof –
 have $A = \text{drop } (\text{length } M) (M' @ \text{Marked } K\ i \# H)$
 using *arg-cong[OF A, of drop (length M)]* by *auto*
 moreover have $\text{drop } (\text{length } M) (M' @ \text{Marked } K\ i \# H) = \text{drop } (\text{length } M) M' @ \text{Marked } K\ i \# H$
 using *nm* by (*metis* (*no-types*, *lifting*) *A drop-Cons' drop-append marked-lit.disc(1) not-gr0*
nth-append nth-append-length nth-mem zero-less-diff)
 finally show *?thesis* by *fast*
 qed

lemma *cdcl_W-stgy-trail-has-new-marked-is-decide-step*:
 assumes $\text{cdcl}_W\text{-stgy } S T$

```

¬ (∃ c. trail S = c @ Marked L i # H @ M) and
(λ a b. cdclW-stgy a b ∧ (∃ c. trail a = c @ Marked L i # H @ M))** T U and
∃ M'. trail U = M' @ Marked L i # H @ M and
lev: cdclW-M-level-inv S
shows ∃ S'. decide S S' ∧ full cdclW-cp S' T ∧ no-step cdclW-cp S
using assms(3,1,2,4,5)
proof induction
  case (step T U)
  then show ?case by fastforce
next
case base
then show ?case
proof (induction rule: cdclW-stgy.induct)
  case (conflict' T) note cp = this(1) and nd = this(2) and M' = this(3) and no-dup = this(3)
  then obtain M' where M': trail T = M' @ Marked L i # H @ M by metis
  obtain M'' where M'': trail T = M'' @ trail S and nm: ∀ m ∈ set M''. ¬ is-marked m
  using cp unfolding full1-def
  by (metis rtranclp-cdclW-cp-dropWhile-trail' tranclp-into-rtranclp)
  have False
  using beginning-not-marked-invert[of M'' trail S M' L i H @ M] M' nm nd unfolding M''
  by fast
  then show ?case by fast
next
case (other' T U') note o = this(1) and ns = this(2) and cp = this(3) and nd = this(4)
  and trU' = this(5)
  have cdclW-cp** T U' using cp unfolding full-def by blast
  from rtranclp-cdclW-cp-dropWhile-trail[OF this]
  have ∃ M'. trail T = M' @ Marked L i # H @ M
  using trU' beginning-not-marked-invert[of - trail T - L i H @ M] by metis
  then obtain M' where M': trail T = M' @ Marked L i # H @ M
  by auto
  with o lev nd cp ns
  show ?case
  proof (induction rule: cdclW-o-induct-lev2)
    case (decide L) note dec = this(1) and cp = this(5) and ns = this(4)
    then have decide S (cons-trail (Marked L (backtrack-lvl S + 1)) (incr-lvl S))
    using decide.hyps decide.intros[of S] by force
    then show ?case using cp decide.premis by (meson decide-state-eq-compatible ns state-eq-ref
      state-eq-sym)
  next
  case (backtrack K j M1 M2 L' D T) note decomp = this(1) and cp = this(3)
    and undef = this(6) and T = this(7) and trT = this(12) and ns = this(4)
  obtain MS3 where MS3: trail S = MS3 @ M2 @ Marked K (Suc j) # M1
  using get-all-marked-decomposition-exists-prepend[OF decomp] by metis
  have tl (M' @ Marked L i # H @ M) = tl M' @ Marked L i # H @ M
  using lev trT T lev undef decomp by (cases M') (auto simp: cdclW-M-level-inv-decomp)
  then have M'': M1 = tl M' @ Marked L i # H @ M
  using arg-cong[OF trT[simplified], of tl] T decomp undef lev
  by (simp add: cdclW-M-level-inv-decomp)
  have False using nd MS3 T undef decomp unfolding M'' by auto
  then show ?case by fast
qed auto
qed
qed

```

lemma *rtrancp-cdcl_W-stgy-with-trail-end-has-trail-end:*

assumes $(\lambda a b. \text{cdcl}_W\text{-stgy } a b \wedge (\exists c. \text{trail } a = c @ \text{Marked } L i \# H @ M))^{**} T U$ **and**
 $\exists M'. \text{trail } U = M' @ \text{Marked } L i \# H @ M$
shows $\exists M'. \text{trail } T = M' @ \text{Marked } L i \# H @ M$
using *assms* **by** (*induction rule: rtrancp-induct*) *auto*

lemma *cdcl_W-o-cannot-learn:*

assumes
cdcl_W-o $y z$ **and**
lev: *cdcl_W-M-level-inv* y **and**
trM: *trail* $y = c @ \text{Marked } Kh i \# H$ **and**
DL: $D + \{\#L\# \} \notin \# \text{learned-clss } y$ **and**
DH: *atms-of* $D \subseteq \text{atm-of 'lits-of } H$ **and**
LH: *atm-of* $L \notin \text{atm-of 'lits-of } H$ **and**
learned: $\forall T. \text{conflicting } y = C\text{-Clause } T \longrightarrow \text{trail } y \models_{as} C\text{Not } T$ **and**
 z : *trail* $z = c' @ \text{Marked } Kh i \# H$

shows $D + \{\#L\# \} \notin \# \text{learned-clss } z$
using *assms*(1–2) *trM DL DH LH learned z*

proof (*induction rule: cdcl_W-o-induct-lev2*)

case (*backtrack* $K j M1 M2 L' D' T$) **note** *decomp* = *this*(1) **and** *confl* = *this*(3) **and** *levD* = *this*(5)
and *undef* = *this*(6) **and** $T = \text{this}(7)$

obtain $M3$ **where** $M3$: *trail* $y = M3 @ M2 @ \text{Marked } K (\text{Suc } j) \# M1$

using *decomp get-all-marked-decomposition-exists-prepend* **by** *metis*

have M : *trail* $y = c @ \text{Marked } Kh i \# H$ **using** *trM* **by** *simp*

have H : *get-all-levels-of-marked* (*trail* y) = *rev* [$1..<1 + \text{backtrack-lvl } y$]

using *lev unfolding cdcl_W-M-level-inv-def* **by** *auto*

have $c' @ \text{Marked } Kh i \# H = \text{Propagated } L' (D' + \{\#L'\# \}) \# \text{trail (reduce-trail-to } M1 y)$

using *backtrack.premis(6) decomp undef T lev* **by** (*force simp: cdcl_W-M-level-inv-def*)

then obtain d **where** d : $M1 = d @ \text{Marked } Kh i \# H$

by (*metis (no-types) decomp in-get-all-marked-decomposition-trail-update-trail list.inject list.sel(3) marked-lit.distinct(1) self-append-conv2 tl-append2*)

have $i \in \text{set (get-all-levels-of-marked (} M3 @ M2 @ \text{Marked } K (\text{Suc } j) \# d @ \text{Marked } Kh i \# H))$
by *auto*

then have $i > 0$ **unfolding** $H[\text{unfolded } M3 d]$ **by** *auto*

show *?case*

proof

assume $D + \{\#L\# \} \in \# \text{learned-clss } T$

then have DLD' : $D + \{\#L\# \} = D' + \{\#L'\# \}$

using *DL T neq0-conv undef decomp lev* **by** (*fastforce simp: cdcl_W-M-level-inv-def*)

have $L\text{-cKh}$: *atm-of* $L \in \text{atm-of 'lits-of } (c @ [\text{Marked } Kh i])$

using *LH learned M DLD'[symmetric] confl* **by** (*fastforce simp add: image-iff*)

have *get-all-levels-of-marked* ($M3 @ M2 @ \text{Marked } K (j + 1) \# M1$)

= *rev* [$1..<1 + \text{backtrack-lvl } y$]

using *lev unfolding cdcl_W-M-level-inv-def M3* **by** *auto*

from *arg-cong[OF this, of $\lambda a. (\text{Suc } j) \in \text{set } a]$* **have** *backtrack-lvl* $y \geq j$ **by** *auto*

have DD' [*simp*]: $D = D'$

proof (*rule ccontr*)

assume $D \neq D'$

then have $L' \in \# D$ **using** DLD' **by** (*metis add.left-neutral count-single count-union diff-union-cancelR neq0-conv union-single-eq-member*)

then have *get-level* $L' (\text{trail } y) \leq \text{get-maximum-level } D (\text{trail } y)$

using *get-maximum-level-ge-get-level* **by** *blast*

moreover {

have *get-maximum-level* $D (\text{trail } y) = \text{get-maximum-level } D H$

```

    using DH unfolding M by (simp add: get-maximum-level-skip-beginning)
  moreover
    have get-all-levels-of-marked (trail y) = rev [1..<1 + backtrack-lvl y]
      using lev unfolding cdclW-M-level-inv-def by auto
    then have get-all-levels-of-marked H = rev [1..< i]
      unfolding M by (auto dest: append-cons-eq-upt-length-i
        simp add: rev-swap[symmetric])
    then have get-maximum-possible-level H < i
      using get-maximum-possible-level-max-get-all-levels-of-marked[of H]  $\langle i > 0 \rangle$  by auto
  ultimately have get-maximum-level D (trail y) < i
    by (metis (full-types) dual-order.strict-trans nat-neq-iff not-le
      get-maximum-possible-level-ge-get-maximum-level) }
  moreover
    have  $L \in \# D'$ 
      by (metis DLD'  $\langle D \neq D' \rangle$  add.left-neutral count-single count-union diff-union-cancelR
        neq0-conv union-single-eq-member)
    then have get-maximum-level D' (trail y)  $\geq$  get-level L (trail y)
      using get-maximum-level-ge-get-level by blast
  moreover {
    have get-all-levels-of-marked (c @ [Marked Kh i]) = rev [i..< backtrack-lvl y + 1]
      using append-cons-eq-upt-length-i-end[of rev (get-all-levels-of-marked H) i
        rev (get-all-levels-of-marked c) Suc 0 Suc (backtrack-lvl y)] H
    unfolding M apply (auto simp add: rev-swap[symmetric])
      by (metis (no-types, hide-lams) Nil-is-append-conv Suc-le-eq less-Suc-eq list.sel(1)
        rev.simps(2) rev-rev-ident upt-Suc upt-rec)
    have get-level L (trail y) = get-level L (c @ [Marked Kh i])
      using L-cKh LH unfolding M by simp
    have get-level L (c @ [Marked Kh i])  $\geq i$ 
      using L-cKh
         $\langle \text{get-all-levels-of-marked } (c @ [\text{Marked Kh } i]) = \text{rev } [i..<\text{backtrack-lvl } y + 1] \rangle$ 
        backtrack.hyps(2) calculation(1,2) by auto
    then have get-level L (trail y)  $\geq i$ 
      using M  $\langle \text{get-level } L (\text{trail } y) = \text{get-level } L (c @ [\text{Marked Kh } i]) \rangle$  by auto }
  moreover have get-maximum-level D' (trail y) < get-level L' (trail y)
    using  $\langle j \leq \text{backtrack-lvl } y \rangle$  backtrack.hyps(2,5) calculation(1-4) by linarith
  ultimately show False using backtrack.hyps(4) by linarith
qed
then have LL': L = L' using DLD' by auto
have nd: no-dup (trail y) using lev unfolding cdclW-M-level-inv-def by auto

{ assume D:  $D' = \{\#\}$ 
  then have j: j = 0 using levD by auto
  have  $\forall m \in \text{set } M1. \neg \text{is-marked } m$ 
    using H unfolding M3 j
    by (auto simp add: rev-swap[symmetric] get-all-levels-of-marked-no-marked
      dest!: append-cons-eq-upt-length-i)
  then have False using d by auto
}
moreover {
  assume D[simp]:  $D' \neq \{\#\}$ 
  have i  $\leq j$ 
    using H unfolding M3 d by (auto simp add: rev-swap[symmetric]
      dest: upt-decomp-lt)
  have j > 0 apply (rule ccontr)
    using H  $\langle i > 0 \rangle$  unfolding M3 d

```

```

    by (auto simp add: rev-swap[symmetric] dest!: upt-decomp-lt)
  obtain L'' where
    L'' ∈ #D' and
    L''D': get-level L'' (trail y) = get-maximum-level D' (trail y)
    using get-maximum-level-exists-lit-of-max-level[OF D, of trail y] by auto
  have L''M: atm-of L'' ∈ atm-of ' lits-of (trail y)
    using get-rev-level-ge-0-atm-of-in[of 0 L'' rev (trail y)] ⟨j>0⟩ levD L''D' by auto
  then have L'' ∈ lits-of (Marked Kh i # d)
  proof -
    {
      assume L''H: atm-of L'' ∈ atm-of ' lits-of H
      have get-all-levels-of-marked H = rev [1..i]
        using H unfolding M
        by (auto simp add: rev-swap[symmetric] dest!: append-cons-eq-upt-length-i)
      moreover have get-level L'' (trail y) = get-level L'' H
        using L''H unfolding M by simp
      ultimately have False
        using levD ⟨j>0⟩ get-rev-level-in-levels-of-marked[of L'' 0 rev H] ⟨i ≤ j⟩
        unfolding L''D'[symmetric] nd by auto
    }
    then show ?thesis
      using DD' DH ⟨L'' ∈ # D'⟩ atm-of-lit-in-atms-of contra-subsetD by metis
  qed
  then have False
    using DH ⟨L'' ∈ #D'⟩ nd unfolding M3 d
    by (auto simp add: atms-of-def image-iff image-subset-iff lits-of-def)
}
ultimately show False by blast
qed
qed auto

```

lemma *cdcl_W-stgy-with-trail-end-has-not-been-learned*:

```

  assumes cdclW-stgy y z and
  cdclW-M-level-inv y and
  trail y = c @ Marked Kh i # H and
  D + {#L#} ∉ # learned-clss y and
  DH: atms-of D ⊆ atm-of ' lits-of H and
  LH: atm-of L ∉ atm-of ' lits-of H and
  ∀ T. conflicting y = C-Clause T ⟶ trail y ⊨as CNot T and
  trail z = c' @ Marked Kh i # H
  shows D + {#L#} ∉ # learned-clss z
  using assms
proof induction
  case conflict'
  then show ?case
    unfolding full1-def using tranclp-cdclW-cp-learned-clause-inv by auto
next
  case (other' T U) note o = this(1) and cp = this(3) and lev = this(4) and trY = this(5) and
  notin = this(6) and DH = this(7) and LH = this(8) and confl = this(9) and trU = this(10)
  obtain c' where c': trail T = c' @ Marked Kh i # H
    using cp beginning-not-marked-invert[of - trail T c' Kh i H]
    rtranclp-cdclW-cp-dropWhile-trail[of T U] unfolding trU full-def by fastforce
  show ?case
    using cdclW-o-cannot-learn[OF o lev trY notin DH LH confl c']
    rtranclp-cdclW-cp-learned-clause-inv cp unfolding full-def by auto

```

qed

lemma *rtranclp-cdcl_W-stgy-with-trail-end-has-not-been-learned*:

assumes $(\lambda a b. \text{cdcl}_W\text{-stgy } a b \wedge (\exists c. \text{trail } a = c @ \text{Marked } K i \# H @ []))^{**} S z$ **and**
cdcl_W-all-struct-inv *S* **and**
trail *S* = *c* @ *Marked* *K i* # *H* **and**
D + {#*L*#} $\notin \#$ *learned-clss* *S* **and**
DH: *atms-of* *D* \subseteq *atm-of* 'lits-of *H* **and**
LH: *atm-of* *L* \notin *atm-of* 'lits-of *H* **and**
 $\exists c'. \text{trail } z = c' @ \text{Marked } K i \# H$
shows *D* + {#*L*#} $\notin \#$ *learned-clss* *z*
using *assms*(1-4,7)

proof (*induction rule: rtranclp-induct*)

case *base*

then show ?*case* **by** *auto*[1]

next

case (*step* *T U*) **note** *st* = *this*(1) **and** *s* = *this*(2) **and** *IH* = *this*(3)[*OF this*(4-6)]

and *lev* = *this*(4) **and** *trS* = *this*(5) **and** *DL-S* = *this*(6) **and** *trU* = *this*(7)

obtain *c* **where** *c*: *trail* *T* = *c* @ *Marked* *K i* # *H* **using** *s* **by** *auto*

obtain *c'* **where** *c'*: *trail* *U* = *c'* @ *Marked* *K i* # *H* **using** *trU* **by** *blast*

have *cdcl_W*^{**} *S T*

proof –

have $\forall p pa. \exists s sa. \forall sb sc sd se. (\neg p^{**} (sb::'st) sc \vee p s sa \vee pa^{**} sb sc)$
 $\wedge (\neg pa s sa \vee \neg p^{**} sd se \vee pa^{**} sd se)$

by (*metis* (*no-types*) *mono-rtranclp*)

then have *cdcl_W-stgy*^{**} *S T*

using *st* **by** *blast*

then show ?*thesis*

using *rtranclp-cdcl_W-stgy-rtranclp-cdcl_W* **by** *blast*

qed

then have *lev'*: *cdcl_W-all-struct-inv* *T*

using *rtranclp-cdcl_W-all-struct-inv-inv*[*of S T*] *lev* **by** *auto*

then have *confl'*: $\forall Ta. \text{conflicting } T = C\text{-Clause } Ta \longrightarrow \text{trail } T \models_{as} C\text{Not } Ta$

unfolding *cdcl_W-all-struct-inv-def* *cdcl_W-conflicting-def* **by** *blast*

show ?*case*

apply (*rule* *cdcl_W-stgy-with-trail-end-has-not-been-learned*[*OF - - c - DH LH confl' c'*])

using *s lev' IH c* **unfolding** *cdcl_W-all-struct-inv-def* **by** *blast*+

qed

lemma *cdcl_W-stgy-new-learned-clause*:

assumes *cdcl_W-stgy* *S T* **and**

lev: *cdcl_W-M-level-inv* *S* **and**

E $\notin \#$ *learned-clss* *S* **and**

E $\in \#$ *learned-clss* *T*

shows $\exists S'. \text{backtrack } S S' \wedge \text{conflicting } S = C\text{-Clause } E \wedge \text{full } \text{cdcl}_W\text{-cp } S' T$

using *assms*

proof *induction*

case *conflict'*

then show ?*case* **unfolding** *full1-def* **by** (*auto* *dest: tranclp-cdcl_W-cp-learned-clause-inv*)

next

case (*other'* *T U*) **note** *o* = *this*(1) **and** *cp* = *this*(3) **and** *not-yet* = *this*(5) **and** *learned* = *this*(6)

have *E* $\in \#$ *learned-clss* *T*

using *learned cp rtranclp-cdcl_W-cp-learned-clause-inv* **unfolding** *full-def* **by** *auto*

then have *backtrack* *S T* **and** *conflicting* *S* = *C-Clause* *E*

using *cdcl_W-o-new-clause-learned-is-backtrack-step*[*OF - not-yet o*] *lev* **by** *blast*+

then show ?case using cp by blast
qed

lemma *cdcl_W-stgy-no-relearned-clause*:

assumes

invR: *cdcl_W-all-struct-inv R* and
st': *cdcl_W-stgy** R S* and
bt: *backtrack S T* and
confl: *conflicting S = C-Clause E* and
already-learned: *E ∈# clauses S* and
R: *trail R = []*

shows *False*

proof –

have *M-lev*: *cdcl_W-M-level-inv R*

using *invR* unfolding *cdcl_W-all-struct-inv-def* by auto

have *cdcl_W-M-level-inv S*

using *M-lev* *assms*(2) *rtranclp-cdcl_W-stgy-consistent-inv* by blast

with *bt* obtain *D L M1 M2-loc K i* where

T: *T ~ cons-trail (Propagated L ((D + {#L#})))*
(reduce-trail-to M1 (add-learned-cls (D + {#L#}))
(update-backtrack-lvl (get-maximum-level D (trail S)) (update-conflicting C-True S)))
and

decomp: *(Marked K (Suc (get-maximum-level D (trail S))) # M1, M2-loc) ∈*
set (get-all-marked-decomposition (trail S)) and

k: *get-level L (trail S) = backtrack-lvl S* and

level: *get-level L (trail S) = get-maximum-level (D + {#L#}) (trail S)* and

confl-S: *conflicting S = C-Clause (D + {#L#})* and

i: *i = get-maximum-level D (trail S)* and

undef: *undefined-lit M1 L*

by (*induction rule: backtrack-induction-lev2*) *metis*

obtain *M2* where

M: *trail S = M2 @ Marked K (Suc i) # M1*

using *get-all-marked-decomposition-exists-prepend*[*OF decomp*] unfolding *i* by (*metis append-assoc*)

have *invS*: *cdcl_W-all-struct-inv S*

using *invR* *rtranclp-cdcl_W-all-struct-inv-inv* *rtranclp-cdcl_W-stgy-rtranclp-cdcl_W st'* by blast

then have *confl*: *cdcl_W-conflicting S* unfolding *cdcl_W-all-struct-inv-def* by blast

then have *trail S ⊨_{as} CNot (D + {#L#})* unfolding *cdcl_W-conflicting-def confl-S* by auto

then have *MD*: *trail S ⊨_{as} CNot D* by auto

have *lev'*: *cdcl_W-M-level-inv S* using *invS* unfolding *cdcl_W-all-struct-inv-def* by blast

have *get-lvls-M*: *get-all-levels-of-marked (trail S) = rev [1..*Suc (backtrack-lvl S)*]*

using *lev'* unfolding *cdcl_W-M-level-inv-def* by auto

have *lev*: *cdcl_W-M-level-inv R* using *invR* unfolding *cdcl_W-all-struct-inv-def* by blast

then have *vars-of-D*: *atms-of D ⊆ atm-of ‘lits-of M1*

using *backtrack-atms-of-D-in-M1*[*OF lev' undef - decomp - - T*] *confl-S* *confl T* *decomp k level*
lev' i undef unfolding *cdcl_W-conflicting-def* by (*auto simp: cdcl_W-M-level-inv-def*)

have *no-dup (trail S)* using *lev'* by (*auto simp: cdcl_W-M-level-inv-decomp*)

have *vars-in-M1*:

$\forall x \in \text{atms-of } D. x \notin \text{atm-of ‘lits-of } (M2 @ [\text{Marked } K (\text{get-maximum-level } D (\text{trail } S) + 1)])$

apply (*rule vars-of-D distinct-atms-of-incl-not-in-other*[*of*
M2 @ Marked K (get-maximum-level D (trail S) + 1) # [] M1 D])

using *(no-dup (trail S)) M vars-of-D* by *simp-all*

```

have  $M1-D$ :  $M1 \models_{as} CNot\ D$ 
  using  $vars-in-M1\ true-annots-remove-if-notin-vars$ [of  $M2\ @\ Marked\ K\ (i + 1)\ \# \ []\ M1\ CNot\ D$ ]
   $\langle trail\ S \models_{as} CNot\ D \rangle\ M$  by simp

have  $get-lvls-M$ :  $get-all-levels-of-marked\ (trail\ S) = rev\ [1..<Suc\ (backtrack-lvl\ S)]$ 
  using  $lev'\ unfolding\ cdcl_W-M-level-inv-def$  by auto
then have  $backtrack-lvl\ S > 0$  unfolding  $M$  by (auto split: split-if-asm simp add: upt.simps(2))

obtain  $M1'\ K'\ Ls$  where
   $M'$ :  $trail\ S = Ls\ @\ Marked\ K'\ (backtrack-lvl\ S)\ \# \ M1'$  and
   $Ls$ :  $\forall l \in set\ Ls.\ \neg\ is-marked\ l$  and
   $set\ M1 \subseteq set\ M1'$ 
proof –
  let  $?Ls = takeWhile\ (Not\ o\ is-marked)\ (trail\ S)$ 
  have  $MLs$ :  $trail\ S = ?Ls\ @\ dropWhile\ (Not\ o\ is-marked)\ (trail\ S)$ 
    by auto
  have  $dropWhile\ (Not\ o\ is-marked)\ (trail\ S) \neq []$  unfolding  $M$  by auto
moreover
  from  $hd-dropWhile[OF\ this]$  have  $is-marked(hd\ (dropWhile\ (Not\ o\ is-marked)\ (trail\ S)))$ 
    by simp
ultimately
  obtain  $K'\ K'k$  where
     $K'k$ :  $dropWhile\ (Not\ o\ is-marked)\ (trail\ S)$ 
       $= Marked\ K'\ K'k\ \# \ tl\ (dropWhile\ (Not\ o\ is-marked)\ (trail\ S))$ 
    by (cases dropWhile (Not o is-marked) (trail S);
      cases hd (dropWhile (Not o is-marked) (trail S)))
    simp-all
  moreover have  $\forall l \in set\ ?Ls.\ \neg is-marked\ l$  using  $set-takeWhileD$  by force
moreover
  have  $get-all-levels-of-marked\ (trail\ S)$ 
     $= K'k\ \# \ get-all-levels-of-marked(tl\ (dropWhile\ (Not\ o\ is-marked)\ (trail\ S)))$ 
  apply (subst MLs, subst K'k)
  using  $calculation(2)$  by (auto simp add: get-all-levels-of-marked-no-marked)
  then have  $K'k = backtrack-lvl\ S$ 
  using  $calculation(2)$  by (auto split: split-if-asm simp add: get-lvls-M upt.simps(2))
moreover have  $set\ M1 \subseteq set\ (tl\ (dropWhile\ (Not\ o\ is-marked)\ (trail\ S)))$ 
  unfolding  $M$  by (induction M2) auto
ultimately show  $?thesis$  using that MLs by metis
qed

have  $get-lvls-M$ :  $get-all-levels-of-marked\ (trail\ S) = rev\ [1..<Suc\ (backtrack-lvl\ S)]$ 
  using  $lev'\ unfolding\ cdcl_W-M-level-inv-def$  by auto
then have  $backtrack-lvl\ S > 0$  unfolding  $M$  by (auto split: split-if-asm simp add: upt.simps(2) i)

have  $M1'-D$ :  $M1' \models_{as} CNot\ D$  using  $M1-D\ \langle set\ M1 \subseteq set\ M1' \rangle$  by (auto intro: true-annots-mono)
have  $-L \in lits-of\ (trail\ S)$  using  $conf\ confl-S$  unfolding  $cdcl_W-conflicting-def$  by auto
have  $lvls-M1'$ :  $get-all-levels-of-marked\ M1' = rev\ [1..<backtrack-lvl\ S]$ 
  using  $get-lvls-M\ Ls$  by (auto simp add: get-all-levels-of-marked-no-marked M'
    split: split-if-asm simp add: upt.simps(2))
have  $L-notin$ :  $atm-of\ L \in atm-of\ 'lits-of\ Ls \vee atm-of\ L = atm-of\ K'$ 
proof (rule ccontr)
  assume  $\neg\ ?thesis$ 
  then have  $atm-of\ L \notin atm-of\ 'lits-of\ (Marked\ K'\ (backtrack-lvl\ S)\ \# \ rev\ Ls)$  by simp
  then have  $get-level\ L\ (trail\ S) = get-level\ L\ M1'$ 
    unfolding  $M'$  by auto

```

```

    then show False using get-level-in-levels-of-marked[of L M1] ⟨backtrack-lvl S > 0⟩
    unfolding k lvs-M1' by auto
qed
obtain Y Z where
  RY: cdclW-stgy** R Y and
  YZ: cdclW-stgy Y Z and
  nt: ¬ (∃ c. trail Y = c @ Marked K' (backtrack-lvl S) # M1' @ []) and
  Z: (λa b. cdclW-stgy a b ∧ (∃ c. trail a = c @ Marked K' (backtrack-lvl S) # M1' @ []))**
    Z S
  using rtrancpl-cdclW-new-marked-at-beginning-is-decide'[OF st' - lev, of Ls K'
    backtrack-lvl S M1' []]
  unfolding R M' by auto
have [simp]: cdclW-M-level-inv Y
  using RY lev rtrancpl-cdclW-stgy-consistent-inv by blast
obtain M' where trZ: trail Z = M' @ Marked K' (backtrack-lvl S) # M1'
  using rtrancpl-cdclW-stgy-with-trail-end-has-trail-end[OF Z] M' by auto
have no-dup (trail Y)
  using RY lev rtrancpl-cdclW-stgy-consistent-inv unfolding cdclW-M-level-inv-def by blast
then obtain Y' where
  dec: decide Y Y' and
  Y'Z: full cdclW-cp Y' Z and
  no-step cdclW-cp Y
  using cdclW-stgy-trail-has-new-marked-is-decide-step[OF YZ nt Z] M' by auto
have trY: trail Y = M1'
proof -
  obtain M' where M: trail Z = M' @ Marked K' (backtrack-lvl S) # M1'
    using rtrancpl-cdclW-stgy-with-trail-end-has-trail-end[OF Z] M' by auto
  obtain M'' where M'': trail Z = M'' @ trail Y' and ∀ m ∈ set M''. ¬ is-marked m
    using Y'Z rtrancpl-cdclW-cp-dropWhile-trail' unfolding full-def by blast
  obtain M''' where trail Y' = M''' @ Marked K' (backtrack-lvl S) # M1'
    using M'' unfolding M
    by (metis (no-types, lifting) ⟨∀ m ∈ set M''. ¬ is-marked m⟩ beginning-not-marked-invert)
  then show ?thesis using dec nt by (induction M''') auto
qed
have Y-CT: conflicting Y = C-True using ⟨decide Y Y'⟩ by auto
have cdclW** R Y by (simp add: RY rtrancpl-cdclW-stgy-rtrancpl-cdclW)
then have init-clss Y = init-clss R using rtrancpl-cdclW-init-clss[of R Y] M-lev by auto
{ assume DL: D + {#L#} ∈ # clauses Y
  have atm-of L ∉ atm-of ' lits-of M1
    apply (rule backtrack-lit-skipped[of - S])
    using decomp i k lev' unfolding cdclW-M-level-inv-def by auto
  then have LM1: undefined-lit M1 L
    by (metis Marked-Propagated-in-iff-in-lits-of atm-of-uminus image-eqI)
  have L-trY: undefined-lit (trail Y) L
    using L-notin ⟨no-dup (trail S)⟩ unfolding defined-lit-map trY M'
    by (auto simp add: image-iff lits-of-def)
  have ∃ Y'. propagate Y Y'
    using propagate-rule[of Y] DL M1'-D L-trY Y-CT trY DL by (metis state-eq-ref)
  then have False using ⟨no-step cdclW-cp Y⟩ propagate' by blast
}
}
moreover {
  assume DL: D + {#L#} ∉ # clauses Y
  have lY-lZ: learned-clss Y = learned-clss Z
    using dec Y'Z rtrancpl-cdclW-cp-learned-clause-inv[of Y' Z] unfolding full-def
    by auto

```

```

have invZ: cdclW-all-struct-inv Z
  by (meson RY YZ invR r-into-rtrancp rtrancp-cdclW-all-struct-inv-inv
      rtrancp-cdclW-stgy-rtrancp-cdclW)
have D + {#L#} ∉ #learned-clss S
  apply (rule rtrancp-cdclW-stgy-with-trail-end-has-not-been-learned[OF Z invZ trZ])
    using DL lY-lZ unfolding clauses-def apply simp
    apply (metis (no-types, lifting) ⟨set M1 ⊆ set M1'⟩ image-mono order-trans
        vars-of-D lits-of-def)
    using L-notin ⟨no-dup (trail S)⟩ unfolding M' by (auto simp add: image-iff lits-of-def)
then have False
  using already-learned DL confl st' M-lev unfolding M'
  by (simp add: ⟨init-clss Y = init-clss R⟩ clauses-def confl-S
      rtrancp-cdclW-stgy-no-more-init-clss)
}
ultimately show False by blast
qed

```

```

lemma rtrancp-cdclW-stgy-distinct-mset-clauses:
  assumes
    invR: cdclW-all-struct-inv R and
    st: cdclW-stgy** R S and
    dist: distinct-mset (clauses R) and
    R: trail R = []
  shows distinct-mset (clauses S)
  using st
proof (induction)
  case base
  then show ?case using dist by simp
next
  case (step S T) note st = this(1) and s = this(2) and IH = this(3)
  from s show ?case
  proof (cases rule: cdclW-stgy.cases)
    case conflict'
    then show ?thesis
      using IH unfolding full1-def by (auto dest: rtrancp-cdclW-cp-no-more-clauses)
  next
    case (other' S') note o = this(1) and full = this(3)
    have [simp]: clauses T = clauses S'
      using full unfolding full-def by (auto dest: rtrancp-cdclW-cp-no-more-clauses)
    show ?thesis
      using o IH
    proof (cases rule: cdclW-o-rule-cases)
      case backtrack
      moreover
        have cdclW-all-struct-inv S
          using invR rtrancp-cdclW-stgy-cdclW-all-struct-inv st by blast
        then have cdclW-M-level-inv S
          unfolding cdclW-all-struct-inv-def by auto
      ultimately obtain E where
        conflicting S = C-Clause E and
        cls-S': clauses S' = {#E#} + clauses S
        using ⟨cdclW-M-level-inv S⟩
        by (induction rule: backtrack-induction-lev2) (auto simp: cdclW-M-level-inv-decomp)
      then have E ∉ #clauses S
        using cdclW-stgy-no-relearned-clause R invR local.backtrack st by blast
    end
  end

```

```

    then show ?thesis using IH by (simp add: distinct-mset-add-single cls-S')
  qed auto
qed
qed

```

```

lemma cdclW-stgy-distinct-mset-clauses:
  assumes
    st: cdclW-stgy** (init-state N) S and
    no-duplicate-clause: distinct-mset N and
    no-duplicate-in-clause: distinct-mset-mset N
  shows distinct-mset (clauses S)
  using rtrancp-cdclW-stgy-distinct-mset-clauses[OF - st] assms
  by (auto simp: cdclW-all-struct-inv-def distinct-cdclW-state-def)

```

17.9 Decrease of a measure

```

fun cdclW-measure where
  cdclW-measure S =
    [(3::nat) ^ (card (atms-of-msu (init-clss S))) - card (set-mset (learned-clss S)),
     if conflicting S = C-True then 1 else 0,
     if conflicting S = C-True then card (atms-of-msu (init-clss S)) - length (trail S)
     else length (trail S)
    ]

```

```

lemma length-model-le-vars-all-inv:
  assumes cdclW-all-struct-inv S
  shows length (trail S) ≤ card (atms-of-msu (init-clss S))
  using assms length-model-le-vars[of S] unfolding cdclW-all-struct-inv-def
  by (auto simp: cdclW-M-level-inv-decomp)
end

```

```

locale cdclW-termination =
  cdclW-ops trail init-clss learned-clss backtrack-lvl conflicting cons-trail tl-trail
  add-init-cls
  add-learned-cls remove-cls update-backtrack-lvl update-conflicting init-state
  restart-state
  for
    trail :: 'st::equal ⇒ ('v::linorder, nat, 'v clause) marked-lits and
    init-clss :: 'st ⇒ 'v clauses and
    learned-clss :: 'st ⇒ 'v clauses and
    backtrack-lvl :: 'st ⇒ nat and
    conflicting :: 'st ⇒ 'v clause conflicting-clause and

    cons-trail :: ('v, nat, 'v clause) marked-lit ⇒ 'st ⇒ 'st and
    tl-trail :: 'st ⇒ 'st and
    add-init-cls :: 'v clause ⇒ 'st ⇒ 'st and
    add-learned-cls :: 'v clause ⇒ 'st ⇒ 'st and
    remove-cls :: 'v clause ⇒ 'st ⇒ 'st and
    update-backtrack-lvl :: nat ⇒ 'st ⇒ 'st and
    update-conflicting :: 'v clause conflicting-clause ⇒ 'st ⇒ 'st and

    init-state :: 'v clauses ⇒ 'st and
    restart-state :: 'st ⇒ 'st
  begin

```

```

lemma learned-clss-less-upper-bound:

```

```

fixes  $S :: 'st$ 
assumes
   $distinct-cdcl_W\text{-state } S$  and
   $\forall s \in \# \text{ learned-clss } S. \neg \text{tautology } s$ 
shows  $card(\text{set-mset } (\text{learned-clss } S)) \leq 3 \wedge card(\text{atms-of-msu } (\text{learned-clss } S))$ 
proof –
  have  $\text{set-mset } (\text{learned-clss } S) \subseteq \text{build-all-simple-clss } (\text{atms-of-msu } (\text{learned-clss } S))$ 
  apply (rule simplified-in-build-all)
  using assms unfolding distinct-cdcl_W-state-def by auto
  then have  $card(\text{set-mset } (\text{learned-clss } S))$ 
     $\leq card(\text{build-all-simple-clss } (\text{atms-of-msu } (\text{learned-clss } S)))$ 
  by (simp add: build-all-simple-clss-finite card-mono)
  then show ?thesis
  by (meson atms-of-ms-finite build-all-simple-clss-card finite-set-mset order-trans)
qed

lemma lexn3[intro!, simp]:
   $a < a' \vee (a = a' \wedge b < b') \vee (a = a' \wedge b = b' \wedge c < c')$ 
   $\implies ([a::nat, b, c], [a', b', c']) \in \text{lexn } \{(x, y). x < y\} \text{ } 3$ 
apply auto
unfolding lexn-conv apply fastforce
unfolding lexn-conv apply auto
apply (metis append.simps(1) append.simps(2)) +
done

lemma cdcl_W-measure-decreasing:
fixes  $S :: 'st$ 
assumes
   $cdcl_W \text{ } S \text{ } S'$  and
  no-restart:
     $\neg(\text{learned-clss } S \subseteq \# \text{ learned-clss } S' \wedge [] = \text{trail } S' \wedge \text{conflicting } S' = C\text{-True})$ 
  and
   $\text{learned-clss } S \subseteq \# \text{ learned-clss } S'$  and
  no-relearn:  $\bigwedge S'. \text{backtrack } S \text{ } S' \implies \forall T. \text{conflicting } S = C\text{-Clause } T \longrightarrow T \notin \# \text{ learned-clss } S$ 
  and
  alien: no-strange-atm  $S$  and
  M-level:  $cdcl_W\text{-M-level-inv } S$  and
  no-taut:  $\forall s \in \# \text{ learned-clss } S. \neg \text{tautology } s$  and
  no-dup:  $distinct-cdcl_W\text{-state } S$  and
  confl:  $cdcl_W\text{-conflicting } S$ 
shows  $(cdcl_W\text{-measure } S', cdcl_W\text{-measure } S) \in \text{lexn } \{(a, b). a < b\} \text{ } 3$ 
using assms(1) M-level assms(2,3)
proof (induct rule: cdcl_W-all-induct-lev2)
  case (propagate  $C \text{ } L$ ) note undef = this(3) and  $T = \text{this}(4)$  and conf = this(5)
  have propa:  $\text{propagate } S \text{ (cons-trail (Propagated } L \text{ (} C + \{\#L\#\}\text{)) } S)$ 
  using propagate-rule[OF - propagate.hyps(1,2)] propagate.hyps by auto
  then have no-dup':  $\text{no-dup } (\text{Propagated } L \text{ (} (C + \{\#L\#\}\text{)) } \# \text{trail } S)$ 
  by (metis M-level cdcl_W-M-level-inv-decomp(2) marked-lit.sel(2) propagate'
    r-into-rtranclp rtranclp-cdcl_W-cp-consistent-inv trail-cons-trail undef)

  let  $?N = \text{init-clss } S$ 
  have no-strange-atm  $(\text{cons-trail } (\text{Propagated } L \text{ (} C + \{\#L\#\}\text{)) } S)$ 
  using alien cdcl_W.propagate cdcl_W-no-strange-atm-inv propa M-level by blast
  then have atm-of ' lits-of  $(\text{Propagated } L \text{ (} (C + \{\#L\#\}\text{)) } \# \text{trail } S)$ 
     $\subseteq \text{atms-of-msu } (\text{init-clss } S)$ 

```

```

    using undef unfolding no-strange-atm-def by auto
  then have card (atm-of ' lits-of (Propagated L ( (C + {#L#})) # trail S))
    ≤ card (atms-of-msu (init-clss S))
    by (meson atms-of-ms-finite card-mono finite-set-mset)
  then have length (Propagated L ( (C + {#L#})) # trail S) ≤ card (atms-of-msu ?N)
    using no-dup-length-eq-card-atm-of-lits-of no-dup' by fastforce
  then have H: card (atms-of-msu (init-clss S)) - length (trail S)
    = Suc (card (atms-of-msu (init-clss S)) - Suc (length (trail S)))
    by simp
  show ?case using conf T undef by (auto simp: H)
next
case (decide L) note conf = this(1) and undef = this(2) and T = this(4)
moreover
  have dec: decide S (cons-trail (Marked L (backtrack-lvl S + 1)) (incr-lvl S))
    using decide.intros decide.hyps by force
  then have cdclW:cdclW S (cons-trail (Marked L (backtrack-lvl S + 1)) (incr-lvl S))
    using cdclW.simps by blast
moreover
  have lev: cdclW-M-level-inv (cons-trail (Marked L (backtrack-lvl S + 1)) (incr-lvl S))
    using cdclW M-level cdclW-consistent-inv[OF cdclW] by auto
  then have no-dup: no-dup (Marked L (backtrack-lvl S + 1) # trail S)
    using undef unfolding cdclW-M-level-inv-def by auto
  have no-strange-atm (cons-trail (Marked L (backtrack-lvl S + 1)) (incr-lvl S))
    using M-level alien calculation(4) cdclW-no-strange-atm-inv by blast
  then have length (Marked L ((backtrack-lvl S) + 1) # (trail S))
    ≤ card (atms-of-msu (init-clss S))
    using no-dup clauses-def undef
    length-model-le-vars[of cons-trail (Marked L (backtrack-lvl S + 1)) (incr-lvl S)]
    by fastforce
  ultimately show ?case using conf by auto
next
case (skip L C' M D) note tr = this(1) and conf = this(2) and T = this(5)
show ?case using conf T unfolding clauses-def by (simp add: tr)
next
case conflict
then show ?case by simp
next
case resolve
then show ?case using finite unfolding clauses-def by simp
next
case (backtrack K i M1 M2 L D T) note decomp = this(1) and conf = this(3) and undef = this(6)
and
  T = this(7) and lev = this(8)
let ?S' = T
have bt: backtrack S ?S'
  using backtrack.hyps backtrack.intros[of S - - - D L K i] by auto
have D + {#L#} ∉ learned-clss S
  using no-relearn conf bt by auto
then have card-T:
  card (set-mset ({#D + {#L#}#} + learned-clss S)) = Suc (card (set-mset (learned-clss S)))
  by (simp add:)
have distinct-cdclW-state ?S'
  using bt M-level distinct-cdclW-state-inv no-dup other by blast
moreover have ∀ s ∈ #learned-clss ?S'. ¬ tautology s
  using learned-clss-are-not-tautologies[OF cdclW.other[OF cdclW-o.bj[OF

```

```

    cdclW-bj.backtrack[OF bt]]] M-level no-taut confl by auto
ultimately have card (set-mset (learned-clss T)) ≤ 3 ^ card (atms-of-msu (learned-clss T))
  by (auto simp: clauses-def learned-clss-less-upper-bound)
then have H: card (set-mset ({#D + {#L#}#} + learned-clss S))
  ≤ 3 ^ card (atms-of-msu ({#D + {#L#}#} + learned-clss S))
  using T undef decomp lev by (auto simp: cdclW-M-level-inv-decomp)
moreover
  have atms-of-msu ({#D + {#L#}#} + learned-clss S) ⊆ atms-of-msu (init-clss S)
  using alien conf unfolding no-strange-atm-def by auto
then have card-f: card (atms-of-msu ({#D + {#L#}#} + learned-clss S))
  ≤ card (atms-of-msu (init-clss S))
  by (meson atms-of-ms-finite card-mono finite-set-mset)
then have (3::nat) ^ card (atms-of-msu ({#D + {#L#}#} + learned-clss S))
  ≤ 3 ^ card (atms-of-msu (init-clss S)) by simp
ultimately have (3::nat) ^ card (atms-of-msu (init-clss S))
  ≥ card (set-mset ({#D + {#L#}#} + learned-clss S))
  using le-trans by blast
then show ?case using decomp undef diff-less-mono2 card-T T lev
  by (auto simp: cdclW-M-level-inv-decomp)
next
  case restart
  then show ?case using alien by (auto simp: state-eq-def simp del: state-simp)
next
  case (forget C T)
  then have C ∈# learned-clss S and C ∉# learned-clss T
  by auto
  then show ?case using forget(9) by (simp add: mset-leD)
qed

```

```

lemma propagate-measure-decreasing:
  fixes S :: 'st
  assumes propagate S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn {(a, b). a < b} 3
  apply (rule cdclW-measure-decreasing)
  using assms(1) propagate apply blast
    using assms(1) apply (auto simp add: propagate.simps)[3]
    using assms(2) apply (auto simp add: cdclW-all-struct-inv-def)
  done

```

```

lemma conflict-measure-decreasing:
  fixes S :: 'st
  assumes conflict S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn {(a, b). a < b} 3
  apply (rule cdclW-measure-decreasing)
  using assms(1) conflict apply blast
    using assms(1) apply (auto simp add: propagate.simps)[3]
    using assms(2) apply (auto simp add: cdclW-all-struct-inv-def)
  done

```

```

lemma decide-measure-decreasing:
  fixes S :: 'st
  assumes decide S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn {(a, b). a < b} 3
  apply (rule cdclW-measure-decreasing)
  using assms(1) decide other apply blast

```



```

    using assms(1) apply (auto simp add: propagate.simps)[3]
    using assms(2) apply (auto simp add: cdclW-all-struct-inv-def)
done

lemma trans-le:
  trans {(a, (b::nat)). a < b}
  unfolding trans-def by auto

lemma cdclW-cp-measure-decreasing:
  fixes S :: 'st
  assumes cdclW-cp S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn {(a, b). a < b} 3
  using assms
proof induction
  case conflict'
  then show ?case using conflict-measure-decreasing by blast
next
  case propagate'
  then show ?case using propagate-measure-decreasing by blast
qed

lemma tranclp-cdclW-cp-measure-decreasing:
  fixes S :: 'st
  assumes cdclW-cp++ S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn {(a, b). a < b} 3
  using assms
proof induction
  case base
  then show ?case using cdclW-cp-measure-decreasing by blast
next
  case (step T U) note st = this(1) and step = this(2) and IH = this(3) and inv = this(4)
  then have (cdclW-measure T, cdclW-measure S) ∈ lexn {a. case a of (a, b) ⇒ a < b} 3 by blast

  moreover have (cdclW-measure U, cdclW-measure T) ∈ lexn {a. case a of (a, b) ⇒ a < b} 3
  using cdclW-cp-measure-decreasing[OF step] rtranclp-cdclW-all-struct-inv-inv inv
  tranclp-cdclW-cp-tranclp-cdclW[OF st]
  unfolding trans-def rtranclp-unfold
  by blast
  ultimately show ?case using lexn-transI[OF trans-le] unfolding trans-def by blast
qed

lemma cdclW-stgy-step-decreasing:
  fixes R S T :: 'st
  assumes cdclW-stgy S T and
  cdclW-stgy** R S
  trail R = [] and
  cdclW-all-struct-inv R
  shows (cdclW-measure T, cdclW-measure S) ∈ lexn {(a, b). a < b} 3
proof -
  have cdclW-all-struct-inv S
  using assms
  by (metis rtranclp-unfold rtranclp-cdclW-all-struct-inv-inv tranclp-cdclW-stgy-tranclp-cdclW)
with assms show ?thesis
proof induction
  case (conflict' V) note cp = this(1) and inv = this(5)

```

```

show ?case
  using tranclp-cdclW-cp-measure-decreasing[OF HOL.conjunct1[OF cp[unfolded full1-def]] inv]
.
next
case (other' T U) note st = this(1) and H = this(4,5,6,7) and cp = this(3)
have cdclW-all-struct-inv T
  using cdclW-all-struct-inv-inv other other'.hyps(1) other'.prems(4) by blast
from tranclp-cdclW-cp-measure-decreasing[OF - this]
have le-or-eq: (cdclW-measure U, cdclW-measure T) ∈ lern {a. case a of (a, b) ⇒ a < b} 3 ∨
  cdclW-measure U = cdclW-measure T
  using cp unfolding full-def rtranclp-unfold by blast
moreover
have cdclW-M-level-inv S
  using cdclW-all-struct-inv-def other'.prems(4) by blast
with st have (cdclW-measure T, cdclW-measure S) ∈ lern {a. case a of (a, b) ⇒ a < b} 3
proof (induction rule:cdclW-o-induct-lev2)
  case (decide T)
  then show ?case using decide-measure-decreasing H by blast
next
case (backtrack K i M1 M2 L D T) note decomp = this(1) and undef = this(6) and T =
this(7)
have bt: backtrack S T
  apply (rule backtrack-rule)
  using backtrack.hyps by auto
then have no-relearn: ∀ T. conflicting S = C-Clause T ⟶ T ∉ # learned-clss S
  using cdclW-stgy-no-relearned-clause[of R S T] H
  unfolding cdclW-all-struct-inv-def clauses-def by auto
have inv: cdclW-all-struct-inv S
  using ⟨cdclW-all-struct-inv S⟩ by blast
show ?case
  apply (rule cdclW-measure-decreasing)
  using bt cdclW-bj.backtrack cdclW-o.bj other apply simp
  using bt T undef decomp inv unfolding cdclW-all-struct-inv-def
  cdclW-M-level-inv-def apply auto[]
  using bt T undef decomp inv unfolding cdclW-all-struct-inv-def
  cdclW-M-level-inv-def apply auto[]
  using bt no-relearn apply auto[]
  using inv unfolding cdclW-all-struct-inv-def apply simp
  using inv unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def apply simp
  using inv unfolding cdclW-all-struct-inv-def apply simp
  using inv unfolding cdclW-all-struct-inv-def apply simp
  using inv unfolding cdclW-all-struct-inv-def by simp
next
case skip
  then show ?case by force
next
case resolve
  then show ?case by force
qed
ultimately show ?case
  by (metis lern-transI transD trans-le)
qed
qed

```

lemma tranclp-cdcl_W-stgy-decreasing:

```

fixes  $R\ S\ T :: 'st$ 
assumes  $cdcl_W\text{-stgy}^{++}\ R\ S$ 
 $trail\ R = []$  and
 $cdcl_W\text{-all-struct-inv}\ R$ 
shows  $(cdcl_W\text{-measure}\ S,\ cdcl_W\text{-measure}\ R) \in le_{rn}\ \{(a,\ b).\ a < b\}\ \exists$ 
using  $assms$ 
apply  $induction$ 
  using  $cdcl_W\text{-stgy-step-decreasing}[of\ R - R]$  apply  $blast$ 
using  $cdcl_W\text{-stgy-step-decreasing}[of\ - - R]$   $trancpl\text{-into-rtrancpl}[of\ cdcl_W\text{-stgy}\ R]$ 
 $le_{rn}\text{-transI}[OF\ trans\text{-le},\ of\ \exists]$  unfolding  $trans\text{-def}$  by  $blast$ 

lemma  $trancpl\text{-}cdcl_W\text{-stgy}\text{-}S0\text{-decreasing}$ :
  fixes  $R\ S\ T :: 'st$ 
  assumes  $pl: cdcl_W\text{-stgy}^{++}\ (init\text{-state}\ N)\ S$  and
   $no\text{-dup}: distinct\text{-mset-mset}\ N$ 
  shows  $(cdcl_W\text{-measure}\ S,\ cdcl_W\text{-measure}\ (init\text{-state}\ N)) \in le_{rn}\ \{(a,\ b).\ a < b\}\ \exists$ 
proof –
  have  $cdcl_W\text{-all-struct-inv}\ (init\text{-state}\ N)$ 
    using  $no\text{-dup}$  unfolding  $cdcl_W\text{-all-struct-inv-def}$  by  $auto$ 
  then show  $?thesis$  using  $pl\ trancpl\text{-}cdcl_W\text{-stgy-decreasing}\ init\text{-state-trail}$  by  $blast$ 
qed

lemma  $wf\text{-}trancpl\text{-}cdcl_W\text{-stgy}$ :
   $wf\ \{(S::'st,\ init\text{-state}\ N) \mid S\ N.\ distinct\text{-mset-mset}\ N \wedge cdcl_W\text{-stgy}^{++}\ (init\text{-state}\ N)\ S\}$ 
  apply  $(rule\ wf\text{-}wf\text{-}if\text{-}measure'\text{-}notation2[of\ le_{rn}\ \{(a,\ b).\ a < b\}\ \exists - - cdcl_W\text{-measure}])$ 
  apply  $(simp\ add: wf\ wf\text{-}le_{rn})$ 
  using  $trancpl\text{-}cdcl_W\text{-stgy}\text{-}S0\text{-decreasing}$  by  $blast$ 
end

end
theory  $DPLL\text{-}CDCL\text{-}W\text{-Implementation}$ 
imports  $Partial\text{-}Annotated\text{-}Clausal\text{-}Logic$ 
begin

```

18 Simple Implementation of the DPLL and CDCL

18.1 Common Rules

18.1.1 Propagation

The following theorem holds:

```

lemma  $lits\text{-of-unfold}[iff]$ :
   $(\forall c \in set\ C.\ -c \in lits\text{-of}\ Ms) \longleftrightarrow Ms \models_{as}\ CNot\ (mset\ C)$ 
  unfolding  $true\text{-annots-def}\ Ball\text{-def}\ true\text{-annot-def}\ CNot\text{-def}\ mem\text{-set-multiset-eq}$  by  $auto$ 

```

The right-hand version is written at a high-level, but only the left-hand side is executable.

```

definition  $is\text{-unit-clause} :: 'a\ literal\ list \Rightarrow ('a,\ 'b,\ 'c)\ marked\text{-lit}\ list \Rightarrow 'a\ literal\ option$ 
where
 $is\text{-unit-clause}\ l\ M =$ 
   $(case\ List.filter\ (\lambda a.\ atm\text{-of}\ a \notin atm\text{-of}\ 'lits\text{-of}\ M)\ l\ of$ 
     $a\ \# [] \Rightarrow if\ M \models_{as}\ CNot\ (mset\ l - \{\#a\# \})\ then\ Some\ a\ else\ None$ 
     $| - \Rightarrow None)$ 

```

```

definition  $is\text{-unit-clause-code} :: 'a\ literal\ list \Rightarrow ('a,\ 'b,\ 'c)\ marked\text{-lit}\ list$ 
   $\Rightarrow 'a\ literal\ option$  where

```

is-unit-clause-code $l\ M =$
 (case *List.filter* ($\lambda a. \text{atm-of } a \notin \text{atm-of ' lits-of } M$) l of
 $a \# [] \Rightarrow \text{if } (\forall c \in \text{set } (\text{remove1 } a\ l). -c \in \text{lits-of } M) \text{ then Some } a \text{ else None}$
 $| - \Rightarrow \text{None}$)

lemma *is-unit-clause-is-unit-clause-code*[code]:

is-unit-clause $l\ M = \text{is-unit-clause-code } l\ M$

proof –

have $1: \bigwedge a. (\forall c \in \text{set } (\text{remove1 } a\ l). -c \in \text{lits-of } M) \longleftrightarrow M \models_{\text{as}} \text{CNot } (\text{mset } l - \{\#a\# \})$

using *lits-of-unfold*[of *remove1 - l*, of *- M*] **by** *simp*

thus *?thesis*

unfolding *is-unit-clause-code-def is-unit-clause-def 1* **by** *blast*

qed

lemma *is-unit-clause-some-undef*:

assumes *is-unit-clause* $l\ M = \text{Some } a$

shows *undefined-lit* $M\ a$

proof –

have (case $[a \leftarrow l . \text{atm-of } a \notin \text{atm-of ' lits-of } M]$ of $[] \Rightarrow \text{None}$
 $| [a] \Rightarrow \text{if } M \models_{\text{as}} \text{CNot } (\text{mset } l - \{\#a\# \}) \text{ then Some } a \text{ else None}$
 $| a \# ab \# xa \Rightarrow \text{Map.empty } xa = \text{Some } a$)

using *assms* **unfolding** *is-unit-clause-def* .

hence $a \in \text{set } [a \leftarrow l . \text{atm-of } a \notin \text{atm-of ' lits-of } M]$

apply (case-tac $[a \leftarrow l . \text{atm-of } a \notin \text{atm-of ' lits-of } M]$)

apply *simp*

apply (case-tac *list*) **by** (auto split: *split-if-asm*)

hence $\text{atm-of } a \notin \text{atm-of ' lits-of } M$ **by** *auto*

thus *?thesis*

by (*simp add: Marked-Propagated-in-iff-in-lits-of*
atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set)

qed

lemma *is-unit-clause-some-CNot*: *is-unit-clause* $l\ M = \text{Some } a \implies M \models_{\text{as}} \text{CNot } (\text{mset } l - \{\#a\# \})$

unfolding *is-unit-clause-def*

proof –

assume (case $[a \leftarrow l . \text{atm-of } a \notin \text{atm-of ' lits-of } M]$ of $[] \Rightarrow \text{None}$
 $| [a] \Rightarrow \text{if } M \models_{\text{as}} \text{CNot } (\text{mset } l - \{\#a\# \}) \text{ then Some } a \text{ else None}$
 $| a \# ab \# xa \Rightarrow \text{Map.empty } xa = \text{Some } a$)

thus *?thesis*

apply (case-tac $[a \leftarrow l . \text{atm-of } a \notin \text{atm-of ' lits-of } M]$, *simp*)

apply *simp*

apply (case-tac *list*) **by** (auto split: *split-if-asm*)

qed

lemma *is-unit-clause-some-in*: *is-unit-clause* $l\ M = \text{Some } a \implies a \in \text{set } l$

unfolding *is-unit-clause-def*

proof –

assume (case $[a \leftarrow l . \text{atm-of } a \notin \text{atm-of ' lits-of } M]$ of $[] \Rightarrow \text{None}$
 $| [a] \Rightarrow \text{if } M \models_{\text{as}} \text{CNot } (\text{mset } l - \{\#a\# \}) \text{ then Some } a \text{ else None}$
 $| a \# ab \# xa \Rightarrow \text{Map.empty } xa = \text{Some } a$)

thus $a \in \text{set } l$

by (case-tac $[a \leftarrow l . \text{atm-of } a \notin \text{atm-of ' lits-of } M]$)

(*fastforce dest: filter-eq-ConsD split: split-if-asm split: list.splits*) +

qed

lemma *is-unit-clause-nil[simp]*: *is-unit-clause* [] *M* = *None*
unfolding *is-unit-clause-def* **by** *auto*

18.1.2 Unit propagation for all clauses

Finding the first clause to propagate

fun *find-first-unit-clause* :: '*a* literal list list \Rightarrow ('*a*, '*b*, '*c*) marked-lit list
 \Rightarrow ('*a* literal \times '*a* literal list) option **where**
find-first-unit-clause (*a* # *l*) *M* =
 (case *is-unit-clause* *a* *M* of
None \Rightarrow *find-first-unit-clause* *l* *M*
 | *Some* *L* \Rightarrow *Some* (*L*, *a*) |
find-first-unit-clause [] - = *None*

lemma *find-first-unit-clause-some*:
find-first-unit-clause *l* *M* = *Some* (*a*, *c*)
 $\implies c \in \text{set } l \wedge M \models_{\text{as}} \text{CNot } (\text{mset } c - \{\#a\# \}) \wedge \text{undefined-lit } M \ a \wedge a \in \text{set } c$
apply (*induction* *l*)
apply *simp*
by (*auto split: option.splits dest: is-unit-clause-some-in is-unit-clause-some-CNot*
is-unit-clause-some-undef)

lemma *propagate-is-unit-clause-not-None*:
assumes *dist: distinct c* **and**
M: M \models_{as} CNot (mset c - {\#a\#}) **and**
undef: undefined-lit M a **and**
ac: a \in set c
shows *is-unit-clause* *c* *M* \neq *None*

proof -
have [*a* ← *c* . atm-of *a* \notin atm-of ' lits-of *M*] = [*a*]
using *assms*
proof (*induction* *c*)
 case *Nil* **thus** ?*case* **by** *simp*
next
 case (*Cons* *ac* *c*)
show ?*case*
proof (*cases* *a* = *ac*)
 case *True*
thus ?*thesis* **using** *Cons*
by (*auto simp del: lits-of-unfold*
simp add: lits-of-unfold[symmetric] Marked-Propagated-in-iff-in-lits-of
atm-of-eq-atm-of atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set)
next
 case *False*
hence *T: mset c* + {\#*ac*\#} - {\#*a*\#} = *mset c* - {\#*a*\#} + {\#*ac*\#}
by (*auto simp add: multiset-eq-iff*)
show ?*thesis* **using** *False Cons*
by (*auto simp add: T atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set*)
qed
qed
thus ?*thesis*
using *M* **unfolding** *is-unit-clause-def* **by** *auto*
qed

lemma *find-first-unit-clause-none*:

$distinct\ c \implies c \in set\ l \implies M \models_{as} CNot\ (mset\ c - \{\#a\# \}) \implies undefined-lit\ M\ a \implies a \in set\ c$
 $\implies find-first-unit-clause\ l\ M \neq None$
by (induction l)
(auto split: option.split simp add: propagate-is-unit-clause-not-None)

18.1.3 Decide

fun find-first-unused-var :: 'a literal list list \Rightarrow 'a literal set \Rightarrow 'a literal option **where**
find-first-unused-var (a # l) M =
(case List.find ($\lambda lit. lit \notin M \wedge \neg lit \notin M$) a of
None \Rightarrow find-first-unused-var l M
| Some a \Rightarrow Some a) |
find-first-unused-var [] - = None

lemma find-none[iff]:
List.find ($\lambda lit. lit \notin M \wedge \neg lit \notin M$) a = None \longleftrightarrow atm-of ' set a \subseteq atm-of ' M
apply (induct a)
using atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
by (force simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set)+

lemma find-some: List.find ($\lambda lit. lit \notin M \wedge \neg lit \notin M$) a = Some b $\implies b \in set\ a \wedge b \notin M \wedge \neg b \notin M$
unfolding find-Some-iff **by** (metis nth-mem)

lemma find-first-unused-var-None[iff]:
find-first-unused-var l M = None $\longleftrightarrow (\forall a \in set\ l. atm-of\ ' set\ a \subseteq atm-of\ ' M)$
by (induct l)
(auto split: option.splits dest!: find-some
simp add: image-subset-iff atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set)

lemma find-first-unused-var-Some-not-all-incl:
assumes find-first-unused-var l M = Some c
shows $\neg(\forall a \in set\ l. atm-of\ ' set\ a \subseteq atm-of\ ' M)$
proof -
have find-first-unused-var l M \neq None
using assms **by** (cases find-first-unused-var l M) auto
thus $\neg(\forall a \in set\ l. atm-of\ ' set\ a \subseteq atm-of\ ' M)$ **by** auto
qed

lemma find-first-unused-var-Some:
find-first-unused-var l M = Some a $\implies (\exists m \in set\ l. a \in set\ m \wedge a \notin M \wedge \neg a \notin M)$
by (induct l) (auto split: option.splits dest: find-some)

lemma find-first-unused-var-undefined:
find-first-unused-var l (lits-of Ms) = Some a $\implies undefined-lit\ Ms\ a$
using find-first-unused-var-Some[of l lits-of Ms a] Marked-Propagated-in-iff-in-lits-of
by blast

end

theory DPLL-W-Implementation

imports DPLL-CDCL-W-Implementation DPLL-W $\sim\sim$ /src/HOL/Library/Code-Target-Numeral

begin

18.2 Simple Implementation of DPLL

18.2.1 Combining the propagate and decide: a DPLL step

definition $DPLL\text{-}step :: int\ dpll_W\text{-}marked\text{-}lits \times int\ literal\ list\ list$

$\Rightarrow int\ dpll_W\text{-}marked\text{-}lits \times int\ literal\ list\ list$ **where**

$DPLL\text{-}step = (\lambda(Ms, N).$

(*case find-first-unit-clause* $N\ Ms$ of
Some $(L, -) \Rightarrow (Propagated\ L\ () \# Ms, N)$
 | $- \Rightarrow$
if $\exists C \in set\ N. (\forall c \in set\ C. -c \in lits\text{-}of\ Ms)$
then
 (*case backtrack-split* Ms of
 ($-, L \# M) \Rightarrow (Propagated\ (-\ (lits\text{-}of\ L))\ () \# M, N)$
 | $(-, -) \Rightarrow (Ms, N)$
)
else
 (*case find-first-unused-var* $N\ (lits\text{-}of\ Ms)$ of
Some $a \Rightarrow (Marked\ a\ () \# Ms, N)$
 | *None* $\Rightarrow (Ms, N))))$

Example of propagation:

value $DPLL\text{-}step\ ([Marked\ (Neg\ 1)\ ()], [[Pos\ (1::int), Neg\ 2]])$

We define the conversion function between the states as defined in *Prop-DPLL* (with multisets) and here (with lists).

abbreviation $toS \equiv \lambda(Ms:: (int, unit, unit)\ marked\text{-}lit\ list)$

$(N:: int\ literal\ list\ list). (Ms, mset\ (map\ mset\ N))$

abbreviation $toS' \equiv \lambda(Ms:: (int, unit, unit)\ marked\text{-}lit\ list,$

$N:: int\ literal\ list\ list). (Ms, mset\ (map\ mset\ N))$

Proof of correctness of $DPLL\text{-}step$

lemma $DPLL\text{-}step\text{-}is\text{-}a\text{-}dpll_W\text{-}step:$

assumes $step: (Ms', N') = DPLL\text{-}step\ (Ms, N)$

and $neg: (Ms, N) \neq (Ms', N')$

shows $dpll_W\ (toS\ Ms\ N)\ (toS\ Ms'\ N')$

proof –

let $?S = (Ms, mset\ (map\ mset\ N))$

{ fix $L\ E$

assume $unit: find\text{-}first\text{-}unit\text{-}clause\ N\ Ms = Some\ (L, E)$

hence $Ms'N: (Ms', N') = (Propagated\ L\ () \# Ms, N)$

using $step$ **unfolding** $DPLL\text{-}step\text{-}def$ **by** $auto$

obtain C **where**

$C: C \in set\ N$ **and**

$Ms: Ms \models_{as} CNot\ (mset\ C - \{\#L\# \})$ **and**

$undef: undefined\text{-}lit\ Ms\ L$ **and**

$L \in set\ C$ **using** $find\text{-}first\text{-}unit\text{-}clause\text{-}some[OF\ unit]$ **by** $metis$

have $dpll_W\ (Ms, mset\ (map\ mset\ N))$

$(Propagated\ L\ () \# fst\ (Ms, mset\ (map\ mset\ N)), snd\ (Ms, mset\ (map\ mset\ N)))$

apply $(rule\ dpll_W.propagate)$

using $Ms\ undef\ C\ (L \in set\ C)$ **unfolding** $mem\text{-}set\text{-}multiset\text{-}eq$ **by** $(auto\ simp\ add: C)$

hence $?thesis$ **using** $Ms'N$ **by** $auto$

}

moreover

{ assume $unit: find\text{-}first\text{-}unit\text{-}clause\ N\ Ms = None$

assume $exC: \exists C \in set\ N. Ms \models_{as} CNot\ (mset\ C)$

then obtain C where $C: C \in \text{set } N$ and $Ms: Ms \models_{as} C \text{Not } (mset\ C)$ by *auto*
 then obtain $L\ M\ M'$ where $bt: \text{backtrack-split } Ms = (M', L \# M)$
 using *step exC neq unfolding DPLL-step-def prod.case unit*
 by *(cases backtrack-split Ms, case-tac b) auto*
 hence *is-marked L* using *backtrack-split-snd-hd-marked[of Ms]* by *auto*
 have 1: $dpll_W\ (Ms, mset\ (map\ mset\ N))$
 $(Propagated\ (-\ lit\ of\ L)\ () \# M, snd\ (Ms, mset\ (map\ mset\ N)))$
 apply *(rule dpll_W.backtrack[OF - (is-marked L), of])*
 using $C\ Ms\ bt$ by *auto*
 moreover have $(Ms', N') = (Propagated\ (-\ (lit\ of\ L))\ () \# M, N)$
 using *step exC unfolding DPLL-step-def bt prod.case unit* by *auto*
 ultimately have *?thesis* by *auto*
 }
 moreover
 { assume *unit: find-first-unit-clause N Ms = None*
 assume *exC: $\neg (\exists C \in \text{set } N. Ms \models_{as} C \text{Not } (mset\ C))$*
 obtain L where *unused: find-first-unused-var N (lits-of Ms) = Some L*
 using *step exC neq unfolding DPLL-step-def prod.case unit*
 by *(cases find-first-unused-var N (lits-of Ms)) auto*
 have $dpll_W\ (Ms, mset\ (map\ mset\ N))$
 $(Marked\ L\ () \# fst\ (Ms, mset\ (map\ mset\ N)), snd\ (Ms, mset\ (map\ mset\ N)))$
 apply *(rule dpll_W.decided[of ?S L])*
 using *find-first-unused-var-Some[OF unused]*
 by *(auto simp add: Marked-Propagated-in-iff-in-lits-of atms-of-ms-def)*
 moreover have $(Ms', N') = (Marked\ L\ () \# Ms, N)$
 using *step exC unfolding DPLL-step-def unused prod.case unit* by *auto*
 ultimately have *?thesis* by *auto*
 }
 ultimately show *?thesis* by *(cases find-first-unit-clause N Ms) auto*
 qed

lemma *DPLL-step-stuck-final-state:*

assumes *step: $(Ms, N) = DPLL\text{-}step\ (Ms, N)$*
 shows *conclusive-dpll_W-state (toS Ms N)*

proof –

have *unit: find-first-unit-clause N Ms = None*
 using *step unfolding DPLL-step-def* by *(auto split:option.splits)*

{ assume *n: $\exists C \in \text{set } N. Ms \models_{as} C \text{Not } (mset\ C)$*
 hence $Ms: (Ms, N) = (\text{case } \text{backtrack-split } Ms \text{ of } (x, []) \Rightarrow (Ms, N) \mid (x, L \# M) \Rightarrow (Propagated\ (-\ lit\ of\ L)\ () \# M, N))$
 using *step unfolding DPLL-step-def* by *(simp add:unit)*

have $snd\ (\text{backtrack-split } Ms) = []$

proof *(cases backtrack-split Ms, cases snd (backtrack-split Ms))*

fix $a\ b$

assume *backtrack-split Ms = (a, b)* and $snd\ (\text{backtrack-split } Ms) = []$

thus $snd\ (\text{backtrack-split } Ms) = []$ by *blast*

next

fix $a\ b\ aa\ list$

assume

bt: backtrack-split Ms = (a, b) and

bt': $snd\ (\text{backtrack-split } Ms) = aa \# list$

hence $Ms: Ms = Propagated\ (-\ lit\ of\ aa)\ () \# list$ using Ms by *auto*

have *is-marked aa* using *backtrack-split-snd-hd-marked[of Ms]* *bt bt'* by *auto*


```

    moreover have fst (backtrack-split Ms) @ aa # list = Ms
      using backtrack-split-list-eq[of Ms] bt' by auto
    ultimately have False unfolding Ms by auto
    thus snd (backtrack-split Ms) = [] by blast
  qed

  hence ?thesis
    using n backtrack-snd-empty-not-marked[of Ms] unfolding conclusive-dpllW-state-def
    by (cases backtrack-split Ms) auto
}
moreover {
  assume n: ¬ (∃ C ∈ set N. Ms ⊨as CNot (mset C))
  hence find-first-unused-var N (lits-of Ms) = None
    using step unfolding DPLL-step-def by (simp add: unit split: option.splits)
  hence a: ∀ a ∈ set N. atm-of 'set a ⊆ atm-of ' (lits-of Ms) by auto
  have fst (toS Ms N) ⊨asm snd (toS Ms N) unfolding true-annots-def CNot-def Ball-def
  proof clarify
    fix x
    assume x: x ∈ set-mset (clauses (toS Ms N))
    hence ¬Ms ⊨as CNot x using n unfolding true-annots-def CNot-def Ball-def by auto
    moreover have total-over-m (lits-of Ms) {x}
      using a x image-iff in-mono atms-of-s-def
      unfolding total-over-m-def total-over-set-def lits-of-def by fastforce
    ultimately show fst (toS Ms N) ⊨ x
      using total-not-CNot[of lits-of Ms x] by (simp add: true-annot-def true-annots-true-cls)
    qed
  hence ?thesis unfolding conclusive-dpllW-state-def by blast
}
ultimately show ?thesis by blast
qed

```

18.2.2 Adding invariants

Invariant tested in the function `function DPLL-ci :: int dpllW-marked-lits ⇒ int literal list list`

```

⇒ int dpllW-marked-lits × int literal list list where
DPLL-ci Ms N =
  (if ¬dpllW-all-inv (Ms, mset (map mset N))
   then (Ms, N)
   else
     let (Ms', N') = DPLL-step (Ms, N) in
     if (Ms', N') = (Ms, N) then (Ms, N) else DPLL-ci Ms' N)
  by fast+

```

termination

```

proof (relation {(S', S). (toS' S', toS' S) ∈ {(S', S). dpllW-all-inv S ∧ dpllW S S'}})
  show wf {(S', S). (toS' S', toS' S) ∈ {(S', S). dpllW-all-inv S ∧ dpllW S S'}}
    using wf-if-measure-f[OF dpllW-wf, of toS'] by auto

```

next

```

fix Ms :: int dpllW-marked-lits and N x xa y
assume ¬ ¬ dpllW-all-inv (toS Ms N)
and step: x = DPLL-step (Ms, N)
and x: (xa, y) = x
and (xa, y) ≠ (Ms, N)
thus ((xa, N), Ms, N) ∈ {(S', S). (toS' S', toS' S) ∈ {(S', S). dpllW-all-inv S ∧ dpllW S S'}}
  using DPLL-step-is-a-dpllW-step dpllW-same-clauses split-conv by fastforce
qed

```

No invariant tested **function** (*domintros*) *DPLL-part*:: *int dpll_W-marked-lits* \Rightarrow *int literal list list*
 \Rightarrow

int dpll_W-marked-lits \times *int literal list list* **where**
DPLL-part *Ms N* =
 (let (*Ms'*, *N'*) = *DPLL-step* (*Ms*, *N*) in
 if (*Ms'*, *N'*) = (*Ms*, *N*) then (*Ms*, *N*) else *DPLL-part* *Ms' N*)
 by *fast+*

lemma *snd-DPLL-step[simp]*:

snd (*DPLL-step* (*Ms*, *N*)) = *N*

unfolding *DPLL-step-def* **by** (*auto split: split-if option.splits prod.splits list.splits*)

lemma *dpll_W-all-inv-implicS-2-eq3-and-dom*:

assumes *dpll_W-all-inv* (*Ms*, *mset* (*map mset N*))

shows *DPLL-ci* *Ms N* = *DPLL-part* *Ms N* \wedge *DPLL-part-dom* (*Ms*, *N*)

using *assms*

proof (*induct rule: DPLL-ci.induct*)

case (1 *Ms N*)

have *snd* (*DPLL-step* (*Ms*, *N*)) = *N* **by** *auto*

then obtain *Ms'* **where** *Ms'*: *DPLL-step* (*Ms*, *N*) = (*Ms'*, *N*) **by** (*case-tac DPLL-step* (*Ms*, *N*)) *auto*

have *inv'*: *dpll_W-all-inv* (*toS Ms' N*) **by** (*metis* (*mono-tags*) 1.prem *DPLL-step-is-a-dpll_W-step Ms'*
dpll_W-all-inv old.prod.inject)

{ **assume** (*Ms'*, *N*) \neq (*Ms*, *N*)

hence *DPLL-ci* *Ms' N* = *DPLL-part* *Ms' N* \wedge *DPLL-part-dom* (*Ms'*, *N*) **using** 1(1)[*of - Ms' N*]

Ms'

1(2) *inv'* **by** *auto*

hence *DPLL-part-dom* (*Ms*, *N*) **using** *DPLL-part.domintros Ms'* **by** *fastforce*

moreover have *DPLL-ci* *Ms N* = *DPLL-part* *Ms N* **using** 1.prem *DPLL-part.psims Ms'*

\langle *DPLL-ci* *Ms' N* = *DPLL-part* *Ms' N* \wedge *DPLL-part-dom* (*Ms'*, *N*) \rangle \langle *DPLL-part-dom* (*Ms*, *N*) \rangle **by**

auto

ultimately have *?case* **by** *blast*

}

moreover {

assume (*Ms'*, *N*) = (*Ms*, *N*)

hence *?case* **using** *DPLL-part.domintros DPLL-part.psims Ms'* **by** *fastforce*

}

ultimately show *?case* **by** *blast*

qed

lemma *DPLL-ci-dpll_W-rtrancp*:

assumes *DPLL-ci* *Ms N* = (*Ms'*, *N'*)

shows *dpll_W*** (*toS Ms N*) (*toS Ms' N*)

using *assms*

proof (*induct Ms N arbitrary: Ms' N' rule: DPLL-ci.induct*)

case (1 *Ms N Ms' N'*) **note** *IH* = *this*(1) **and** *step* = *this*(2)

obtain *S*₁ *S*₂ **where** *S*: (*S*₁, *S*₂) = *DPLL-step* (*Ms*, *N*) **by** (*case-tac DPLL-step* (*Ms*, *N*)) *auto*

{ **assume** \neg *dpll_W-all-inv* (*toS Ms N*)

hence (*Ms*, *N*) = (*Ms'*, *N*) **using** *step* **by** *auto*

hence *?case* **by** *auto*

}

moreover

{ **assume** *dpll_W-all-inv* (*toS Ms N*)

and (*S*₁, *S*₂) = (*Ms*, *N*)

hence *?case* **using** *S step* **by** *auto*

```

}
moreover
{ assume  $dpll_W\text{-all-inv}$  (toS Ms N)
  and  $(S_1, S_2) \neq (Ms, N)$ 
  moreover obtain  $S_1' S_2'$  where  $DPLL\text{-ci } S_1 N = (S_1', S_2')$  by (case-tac  $DPLL\text{-ci } S_1 N$ ) auto
  moreover have  $DPLL\text{-ci } Ms N = DPLL\text{-ci } S_1 N$  using  $DPLL\text{-ci.simps}$ [of Ms N] calculation
  proof -
    have (case  $(S_1, S_2)$  of  $(ms, lss) \Rightarrow$ 
      if  $(ms, lss) = (Ms, N)$  then  $(Ms, N)$  else  $DPLL\text{-ci } ms N = DPLL\text{-ci } Ms N$ 
      using  $S DPLL\text{-ci.simps}$ [of Ms N] calculation by presburger
    hence (if  $(S_1, S_2) = (Ms, N)$  then  $(Ms, N)$  else  $DPLL\text{-ci } S_1 N = DPLL\text{-ci } Ms N$ 
      by fastforce
    thus ?thesis
      using calculation(2) by presburger
  qed
ultimately have  $dpll_W^{**}$  (toS  $S_1' N$ ) (toS  $Ms' N$ ) using IH[of  $(S_1, S_2) S_1 S_2$ ] S step by simp

moreover have  $dpll_W$  (toS Ms N) (toS  $S_1 N$ )
  by (metis  $DPLL\text{-step-is-a-dpll}_W\text{-step } S \langle (S_1, S_2) \neq (Ms, N) \rangle$  prod.sel(2) snd-DPLL-step)
ultimately have ?case by (metis (mono-tags, hide-lams) IH S  $\langle (S_1, S_2) \neq (Ms, N) \rangle$ 
   $\langle DPLL\text{-ci } Ms N = DPLL\text{-ci } S_1 N \rangle \langle dpll_W\text{-all-inv (toS Ms N) \rangle$  converse-rtranclp-into-rtranclp
  local.step)
}
ultimately show ?case by blast
qed

lemma  $dpll_W\text{-all-inv-dpll}_W\text{-tranclp-irrefl}$ :
  assumes  $dpll_W\text{-all-inv}$  (Ms, N)
  and  $dpll_W^{++}$  (Ms, N) (Ms, N)
  shows False
proof -
  have 1: wf  $\{(S', S). dpll_W\text{-all-inv } S \wedge dpll_W^{++} S S'\}$  using  $dpll_W\text{-wf-tranclp}$  by auto
  have  $((Ms, N), (Ms, N)) \in \{(S', S). dpll_W\text{-all-inv } S \wedge dpll_W^{++} S S'\}$  using assms by auto
  thus False using wf-not-refl[OF 1] by blast
qed

lemma  $DPLL\text{-ci-final-state}$ :
  assumes step:  $DPLL\text{-ci } Ms N = (Ms, N)$ 
  and inv:  $dpll_W\text{-all-inv}$  (toS Ms N)
  shows conclusive- $dpll_W\text{-state}$  (toS Ms N)
proof -
  have st:  $dpll_W^{**}$  (toS Ms N) (toS Ms N) using  $DPLL\text{-ci-dpll}_W\text{-rtranclp}$ [OF step] .
  have  $DPLL\text{-step}$  (Ms, N) = (Ms, N)
  proof (rule ccontr)
    obtain  $Ms' N'$  where  $Ms' N'$ :  $(Ms', N') = DPLL\text{-step}$  (Ms, N)
    by (case-tac  $DPLL\text{-step}$  (Ms, N)) auto
    assume  $\neg$  ?thesis
    hence  $DPLL\text{-ci } Ms' N = (Ms, N)$  using step inv st  $Ms' N$ [symmetric] by fastforce
    hence  $dpll_W^{++}$  (toS Ms N) (toS Ms N)
    by (metis  $DPLL\text{-ci-dpll}_W\text{-rtranclp } DPLL\text{-step-is-a-dpll}_W\text{-step } Ms' N \langle DPLL\text{-step (Ms, N) } \neq (Ms, N) \rangle$ 
      prod.sel(2) rtranclp-into-tranclp2 snd-DPLL-step)
    thus False using  $dpll_W\text{-all-inv-dpll}_W\text{-tranclp-irrefl inv}$  by auto
  qed
  thus ?thesis using  $DPLL\text{-step-stuck-final-state}$ [of Ms N] by simp

```

qed

lemma *DPLL-step-obtains*:

obtains Ms' where $(Ms', N) = DPLL\text{-}step\ (Ms, N)$
 unfolding *DPLL-step-def* by (metis (no-types, lifting) *DPLL-step-def prod.collapse snd-DPLL-step*)

lemma *DPLL-ci-obtains*:

obtains Ms' where $(Ms', N) = DPLL\text{-}ci\ Ms\ N$

proof (induct rule: *DPLL-ci.induct*)

case (1 $Ms\ N$) note $IH = this(1)$ and $that = this(2)$

obtain S where $SN: (S, N) = DPLL\text{-}step\ (Ms, N)$ using *DPLL-step-obtains* by metis

{ assume $\neg dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N)$

hence ?case using *that* by auto

}

moreover {

assume $n: (S, N) \neq (Ms, N)$

and $inv: dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N)$

have $\exists ms. DPLL\text{-}step\ (Ms, N) = (ms, N)$

by (metis $\langle \bigwedge thesisa. (\bigwedge S. (S, N) = DPLL\text{-}step\ (Ms, N) \implies thesisa) \implies thesisa \rangle$)

hence ?thesis

using *IH that* by fastforce

}

moreover {

assume $n: (S, N) = (Ms, N)$

hence ?case using *SN that* by fastforce

}

ultimately show ?case by blast

qed

lemma *DPLL-ci-no-more-step*:

assumes *step*: $DPLL\text{-}ci\ Ms\ N = (Ms', N')$

shows $DPLL\text{-}ci\ Ms'\ N' = (Ms', N')$

using *assms*

proof (induct arbitrary: $Ms'\ N'$ rule: *DPLL-ci.induct*)

case (1 $Ms\ N\ Ms'\ N'$) note $IH = this(1)$ and $step = this(2)$

obtain S_1 where $S: (S_1, N) = DPLL\text{-}step\ (Ms, N)$ using *DPLL-step-obtains* by auto

{ assume $\neg dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N)$

hence ?case using *step* by auto

}

moreover {

assume $dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N)$

and $(S_1, N) = (Ms, N)$

hence ?case using *S step* by auto

}

moreover

{ assume $inv: dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N)$

assume $n: (S_1, N) \neq (Ms, N)$

obtain S_1' where $SS: (S_1', N) = DPLL\text{-}ci\ S_1\ N$ using *DPLL-ci-obtains* by blast

moreover have $DPLL\text{-}ci\ Ms\ N = DPLL\text{-}ci\ S_1\ N$

proof –

have (case (S_1, N) of $(ms, lss) \Rightarrow$ if $(ms, lss) = (Ms, N)$ then (Ms, N) else $DPLL\text{-}ci\ ms\ N$)
 $= DPLL\text{-}ci\ Ms\ N$

using *S DPLL-ci.simps[of Ms N] calculation inv* by presburger

hence (if $(S_1, N) = (Ms, N)$ then (Ms, N) else $DPLL\text{-}ci\ S_1\ N = DPLL\text{-}ci\ Ms\ N$)

```

    by fastforce
  thus ?thesis
    using calculation n by presburger
qed
moreover
  have  $DPLL\text{-}ci\ S_1' N = (S_1', N)$  using step IH[OF - - S n SS[symmetric]] inv by blast
  ultimately have ?case using step by fastforce
}
ultimately show ?case by blast
qed

```

lemma *DPLL-part-dpll_W-all-inv-final*:

```

  fixes M Ms': (int, unit, unit) marked-lit list and
    N :: int literal list list
  assumes inv: dpllW-all-inv (Ms, mset (map mset N))
  and MsN: DPLL-part Ms N = (Ms', N)
  shows conclusive-dpllW-state (toS Ms' N) ∧ dpllW** (toS Ms N) (toS Ms' N)
proof -
  have 2: DPLL-ci Ms N = DPLL-part Ms N using inv dpllW-all-inv-implicS-2-eq3-and-dom by blast
  hence star: dpllW** (toS Ms N) (toS Ms' N) unfolding MsN using DPLL-ci-dpllW-rtranclp by blast
  hence inv': dpllW-all-inv (toS Ms' N) using inv rtranclp-dpllW-all-inv by blast
  show ?thesis using star DPLL-ci-final-state[OF DPLL-ci-no-more-step inv'] 2 unfolding MsN by blast
qed

```

Embedding the invariant into the type

Defining the type `typedef dpllW-state =`

```

  {(M::(int, unit, unit) marked-lit list, N::int literal list list).
   dpllW-all-inv (toS M N)}

```

`morphisms rough-state-of state-of`

proof

```

  show ([], []) ∈ {(M, N). dpllW-all-inv (toS M N)} by (auto simp add: dpllW-all-inv-def)

```

qed

lemma

```

  DPLL-part-dom ([], N)

```

```

  using assms dpllW-all-inv-implicS-2-eq3-and-dom[of [] N] by (simp add: dpllW-all-inv-def)

```

Some type classes `instantiation dpllW-state :: equal`

begin

```

definition equal-dpllW-state :: dpllW-state ⇒ dpllW-state ⇒ bool where
  equal-dpllW-state S S' = (rough-state-of S = rough-state-of S')

```

instance

```

  by standard (simp add: rough-state-of-inject equal-dpllW-state-def)

```

end

DPLL **definition** *DPLL-step'* :: dpll_W-state ⇒ dpll_W-state **where**

```

  DPLL-step' S = state-of (DPLL-step (rough-state-of S))

```

declare *rough-state-of-inverse*[simp]

lemma *DPLL-step-dpll_W-conc-inv*:

```

DPLL-step (rough-state-of S) ∈ {(M, N). dpllW-all-inv (toS M N)}
by (smt DPLL-ci.simps DPLL-ci-dpllW-rtrancpl case-prodE case-prodI2 rough-state-of
    mem-Collect-eq old.prod.case prod.sel(2) rtrancpl-dpllW-all-inv snd-DPLL-step)

lemma rough-state-of-DPLL-step'-DPLL-step[simp]:
  rough-state-of (DPLL-step' S) = DPLL-step (rough-state-of S)
  using DPLL-step-dpllW-conc-inv DPLL-step'-def state-of-inverse by auto

function DPLL-tot:: dpllW-state ⇒ dpllW-state where
  DPLL-tot S =
    (let S' = DPLL-step' S in
     if S' = S then S else DPLL-tot S')
  by fast+
termination
proof (relation {(T', T).
  (rough-state-of T', rough-state-of T)
  ∈ {(S', S). (toS' S', toS' S)
    ∈ {(S', S). dpllW-all-inv S ∧ dpllW S S'}}})
show wf {(b, a).
  (rough-state-of b, rough-state-of a)
  ∈ {(b, a). (toS' b, toS' a)
    ∈ {(b, a). dpllW-all-inv a ∧ dpllW a b}}})
  using wf-if-measure-f[OF wf-if-measure-f[OF dpllW-wf, of toS'], of rough-state-of] .
next
fix S x
assume x: x = DPLL-step' S
and x ≠ S
have dpllW-all-inv (case rough-state-of S of (Ms, N) ⇒ (Ms, mset (map mset N)))
  by (metis (no-types, lifting) case-prodE mem-Collect-eq old.prod.case rough-state-of)
moreover have dpllW (case rough-state-of S of (Ms, N) ⇒ (Ms, mset (map mset N)))
  (case rough-state-of (DPLL-step' S) of (Ms, N) ⇒ (Ms, mset (map mset N)))
proof -
  obtain Ms N where Ms: (Ms, N) = rough-state-of S by (cases rough-state-of S) auto
  have dpllW-all-inv (toS' (Ms, N)) using calculation unfolding Ms by blast
  moreover obtain Ms' N' where Ms': (Ms', N') = rough-state-of (DPLL-step' S)
  by (cases rough-state-of (DPLL-step' S)) auto
  ultimately have dpllW-all-inv (toS' (Ms', N')) unfolding Ms'
  by (metis (no-types, lifting) case-prod-unfold mem-Collect-eq rough-state-of)

  have dpllW (toS Ms N) (toS Ms' N')
  apply (rule DPLL-step-is-a-dpllW-step[of Ms' N' Ms N])
  unfolding Ms Ms' using ⟨x ≠ S⟩ rough-state-of-inject x by fastforce+
  thus ?thesis unfolding Ms[symmetric] Ms'[symmetric] by auto
qed
ultimately show (x, S) ∈ {(T', T). (rough-state-of T', rough-state-of T)
  ∈ {(S', S). (toS' S', toS' S) ∈ {(S', S). dpllW-all-inv S ∧ dpllW S S'}}})
  by (auto simp add: x)
qed

lemma [code]:
  DPLL-tot S =
    (let S' = DPLL-step' S in
     if S' = S then S else DPLL-tot S') by auto

lemma DPLL-tot-DPLL-step-DPLL-tot[simp]: DPLL-tot (DPLL-step' S) = DPLL-tot S

```

apply (*cases* $DPLL\text{-}step' S = S$)
apply *simp*
unfolding $DPLL\text{-}tot.simps[of S]$ **by** (*simp del: DPLL-tot.simps*)

lemma $DOPLL\text{-}step'\text{-}DPLL\text{-}tot[simp]$:
 $DPLL\text{-}step' (DPLL\text{-}tot S) = DPLL\text{-}tot S$
by (*rule DPLL-tot.induct[of $\lambda S. DPLL\text{-}step' (DPLL\text{-}tot S) = DPLL\text{-}tot S S]$*)
(metis (full-types) DPLL-tot.simps)

lemma $DPLL\text{-}tot\text{-}final\text{-}state$:
assumes $DPLL\text{-}tot S = S$
shows $conclusive\text{-}dpll_W\text{-}state (toS' (rough\text{-}state\text{-}of S))$
proof –
have $DPLL\text{-}step' S = S$ **using** *assms[symmetric] DOPLL-step'-DPLL-tot* **by** *metis*
hence $DPLL\text{-}step (rough\text{-}state\text{-}of S) = (rough\text{-}state\text{-}of S)$
unfolding $DPLL\text{-}step'\text{-}def$ **using** $DPLL\text{-}step\text{-}dpll_W\text{-}conc\text{-}inv$ $rough\text{-}state\text{-}of\text{-}inverse$
by (*metis rough-state-of-DPLL-step'-DPLL-step*)
thus *?thesis*
by (*metis (mono-tags, lifting) DPLL-step-stuck-final-state old.prod.exhaust split-conv*)
qed

lemma $DPLL\text{-}tot\text{-}star$:
assumes $rough\text{-}state\text{-}of (DPLL\text{-}tot S) = S'$
shows $dpll_W^{**} (toS' (rough\text{-}state\text{-}of S)) (toS' S')$
using *assms*
proof (*induction arbitrary: S' rule: DPLL-tot.induct*)
case ($1 S S'$)
let $?x = DPLL\text{-}step' S$
{ assume $?x = S$
then have $?case$ **using** $1(2)$ **by** *simp*
}
moreover {
assume $S: ?x \neq S$
have $?case$
apply (*cases* $DPLL\text{-}step' S = S$)
using S **apply** *blast*
by (*smt 1.IH 1.prem DPLL-step-is-a-dpll_W-step DPLL-tot.simps case-prodE2*
 $rough\text{-}state\text{-}of\text{-}DPLL\text{-}step'\text{-}DPLL\text{-}step$ $rtranclp.rtrancl\text{-}into\text{-}rtrancl$ $rtranclp.rtrancl\text{-}refl$
 $rtranclp\text{-}idemp$ $split\text{-}conv$)
}
ultimately show $?case$ **by** *auto*
qed

lemma $rough\text{-}state\text{-}of\text{-}rough\text{-}state\text{-}of\text{-}nil[simp]$:
 $rough\text{-}state\text{-}of (state\text{-}of ([], N)) = ([], N)$
apply (*rule DPLL-W-Implementation.dpll_W-state.state-of-inverse*)
unfolding $dpll_W\text{-}all\text{-}inv\text{-}def$ **by** *auto*

Theorem of correctness

lemma $DPLL\text{-}tot\text{-}correct$:
assumes $rough\text{-}state\text{-}of (DPLL\text{-}tot (state\text{-}of ([], N))) = (M, N')$
and $(M', N'') = toS' (M, N')$
shows $M' \models_{asm} N'' \longleftrightarrow \text{satisfiable } (set\text{-}mset N'')$

proof –

have $dpll_W^{**}$ (toS' (\square , N)) (toS' (M , N')) **using** $DPLL-tot-star[OF\ assms(1)]$ **by** *auto*
moreover have $conclusive-dpll_W-state$ (toS' (M , N'))
using $DPLL-tot-final-state$ **by** ($metis$ ($mono-tags$, $lifting$) $DOPLL-step'-DPLL-tot$ $DPLL-tot.simps$ $assms(1)$)
ultimately show $?thesis$ **using** $dpll_W-conclusive-state-correct$ **by** (smt $DPLL-ci.simps$ $DPLL-ci-dpll_W-rtrancpl$ $assms(2)$ $dpll_W-all-inv-def$ $prod.case$ $prod.sel(1)$ $prod.sel(2)$ $rtrancpl-dpll_W-inv(3)$ $rtrancpl-dpll_W-inv-starting-from-0$)

qed

18.2.3 Code export

A conversion to $DPLL-W$ -Implementation. $dpll_W-state$ **definition** $Con :: (int, unit, unit) \text{ marked-lit } list \times int \text{ literal list list}$

$\Rightarrow dpll_W-state$ **where**

$Con\ xs = state-of$ ($if\ dpll_W-all-inv$ (toS ($fst\ xs$) ($snd\ xs$)) $then\ xs$ $else$ (\square , \square))

lemma [*code abstype*]:

Con ($rough-state-of\ S$) = S

using $rough-state-of[of\ S]$ **unfolding** $Con-def$ **by** *auto*

declare $rough-state-of-DPLL-step'-DPLL-step$ [*code abstract*]

lemma $Con-DPLL-step-rough-state-of-state-of[simp]$:

Con ($DPLL-step$ ($rough-state-of\ s$)) = $state-of$ ($DPLL-step$ ($rough-state-of\ s$))

unfolding $Con-def$ **by** ($metis$ ($mono-tags$, $lifting$) $DPLL-step-dpll_W-conc-inv$ $mem-Collect-eq$ $prod.case-eq-if$)

A slightly different version of $DPLL-tot$ where the returned boolean indicates the result.

definition $DPLL-tot-rep$ **where**

$DPLL-tot-rep\ S =$

(let (M , N) = ($rough-state-of$ ($DPLL-tot\ S$)) in ($\forall A \in set\ N. (\exists a \in set\ A. a \in lits-of\ (M)), M$))

One version of the generated SML code is here, but not included in the generated document. The only differences are:

- export $'a\ literal$ from the SML Module *Clausal-Logic*;
- export the constructor Con from *DPLL-W-Implementation*;
- export the int constructor from *Arith*.

All these allows to test on the code on some examples.

end

theory *CDCL-W-Implementation*

imports *DPLL-CDCL-W-Implementation* *CDCL-W-Termination*

begin

notation $image-mset$ (**infixr** $'\#$ 90)

type-synonym $'a\ cdcl_W-mark$ = $'a\ clause$

type-synonym $cdcl_W-marked-level$ = nat

type-synonym $'v\ cdcl_W-marked-lit$ = ($'v$, $cdcl_W-marked-level$, $'v\ cdcl_W-mark$) $marked-lit$

type-synonym $'v\ cdcl_W-marked-lits$ = ($'v$, $cdcl_W-marked-level$, $'v\ cdcl_W-mark$) $marked-lits$

type-synonym $'v\ cdcl_W-state$ =

'v cdcl_W-marked-lits × 'v clauses × 'v clauses × nat × 'v clause conflicting-clause

abbreviation *trail* :: 'a × 'b × 'c × 'd × 'e ⇒ 'a **where**
trail ≡ (λ(M, -). M)

abbreviation *cons-trail* :: 'a ⇒ 'a list × 'b × 'c × 'd × 'e ⇒ 'a list × 'b × 'c × 'd × 'e **where**
cons-trail ≡ (λL (M, S). (L#M, S))

abbreviation *tl-trail* :: 'a list × 'b × 'c × 'd × 'e ⇒ 'a list × 'b × 'c × 'd × 'e **where**
tl-trail ≡ (λ(M, S). (tl M, S))

abbreviation *clauses* :: 'a × 'b × 'c × 'd × 'e ⇒ 'b **where**
clauses ≡ λ(M, N, -). N

abbreviation *learned-clss* :: 'a × 'b × 'c × 'd × 'e ⇒ 'c **where**
learned-clss ≡ λ(M, N, U, -). U

abbreviation *backtrack-lvl* :: 'a × 'b × 'c × 'd × 'e ⇒ 'd **where**
backtrack-lvl ≡ λ(M, N, U, k, -). k

abbreviation *update-backtrack-lvl* :: 'd ⇒ 'a × 'b × 'c × 'd × 'e ⇒ 'a × 'b × 'c × 'd × 'e **where**
update-backtrack-lvl ≡ λk (M, N, U, -, S). (M, N, U, k, S)

abbreviation *conflicting* :: 'a × 'b × 'c × 'd × 'e ⇒ 'e **where**
conflicting ≡ λ(M, N, U, k, D). D

abbreviation *update-conflicting* :: 'e ⇒ 'a × 'b × 'c × 'd × 'e ⇒ 'a × 'b × 'c × 'd × 'e **where**
update-conflicting ≡ λS (M, N, U, k, -). (M, N, U, k, S)

abbreviation *S0-cdcl_W N* ≡ (([], N, {#}, 0, C-True):: 'v cdcl_W-state)

abbreviation *add-learned-cls* **where**
add-learned-cls ≡ λC (M, N, U, S). (M, N, {#C#} + U, S)

abbreviation *remove-cls* **where**
remove-cls ≡ λC (M, N, U, S). (M, remove-mset C N, remove-mset C U, S)
interpretation *cdcl_W*: *state_W trail clauses learned-clss backtrack-lvl conflicting*
λL (M, S). (L # M, S)
λ(M, S). (tl M, S)
λC (M, N, S). (M, {#C#} + N, S)
λC (M, N, U, S). (M, N, {#C#} + U, S)
λC (M, N, U, S). (M, remove-mset C N, remove-mset C U, S)
λ(k::nat) (M, N, U, -, D). (M, N, U, k, D)
λD (M, N, U, k, -). (M, N, U, k, D)
λN. ([], N, {#}, 0, C-True)
λ(-, N, U, -). ([], N, U, 0, C-True)

by *unfold-locales auto*

lemma *trail-conv*: *trail* (M, N, U, k, D) = M **and**
clauses-conv: *clauses* (M, N, U, k, D) = N **and**
learned-clss-conv: *learned-clss* (M, N, U, k, D) = U **and**
conflicting-conv: *conflicting* (M, N, U, k, D) = D **and**
backtrack-lvl-conv: *backtrack-lvl* (M, N, U, k, D) = k

by auto
lemma state-conv:
 $S = (\text{trail } S, \text{clauses } S, \text{learned-clss } S, \text{backtrack-lvl } S, \text{conflicting } S)$
 by (cases S) auto

interpretation cdcl_W -termination trail clauses learned-clss backtrack-lvl conflicting

$\lambda L (M, S). (L \# M, S)$
 $\lambda (M, S). (\text{tl } M, S)$
 $\lambda C (M, N, S). (M, \{\#C\# \} + N, S)$
 $\lambda C (M, N, U, S). (M, N, \{\#C\# \} + U, S)$
 $\lambda C (M, N, U, S). (M, \text{remove-mset } C \ N, \text{remove-mset } C \ U, S)$
 $\lambda (k::\text{nat}) (M, N, U, -, D). (M, N, U, k, D)$
 $\lambda D (M, N, U, k, -). (M, N, U, k, D)$
 $\lambda N. ([], N, \{\#\}, 0, C\text{-True})$
 $\lambda (-, N, U, -). ([], N, U, 0, C\text{-True})$
 by intro-locales

lemmas $\text{cdcl}_W.\text{clauses-def}[\text{simp}]$

lemma $\text{cdcl}_W.\text{state-eq-equality}[\text{iff}]$: $\text{cdcl}_W.\text{state-eq } S \ T \longleftrightarrow S = T$
unfolding $\text{cdcl}_W.\text{state-eq-def}$ **by** (cases S, cases T) auto
declare $\text{cdcl}_W.\text{state-simp}[\text{simp del}]$

18.3 CDCL Implementation

18.3.1 Definition of the rules

Types **lemma** true-clss-remdups[simp]:
 $I \models s \ (mset \circ \text{remdups}) \ 'N \longleftrightarrow I \models s \ mset \ 'N$
by (simp add: true-clss-def)

lemma satisfiable-mset-remdups[simp]:
 $\text{satisfiable } ((mset \circ \text{remdups}) \ 'N) \longleftrightarrow \text{satisfiable } (mset \ 'N)$
unfolding satisfiable-carac[symmetric] **by** simp

declare mset-map[symmetric, simp]

value backtrack-split [Marked (Pos (Suc 0)) Level]
value $\exists C \in \text{set } [[\text{Pos } (Suc \ 0), \text{Neg } (Suc \ 0)]] . (\forall c \in \text{set } C. -c \in \text{lits-of } [\text{Marked } (Pos \ (Suc \ 0)) \ \text{Level}])$

type-synonym $\text{cdcl}_W.\text{state-inv-st} = (\text{nat}, \text{nat}, \text{nat literal list}) \text{ marked-lit list} \times \text{nat literal list list}$
 $\times \text{nat literal list list} \times \text{nat} \times \text{nat literal list conflicting-clause}$

We need some functions to convert between our abstract state $\text{nat } \text{cdcl}_W.\text{state}$ and the concrete state $\text{cdcl}_W.\text{state-inv-st}$.

fun convert :: ('a, 'b, 'c list) marked-lit \Rightarrow ('a, 'b, 'c multiset) marked-lit **where**
 convert (Propagated L C) = Propagated L (mset C) |
 convert (Marked K i) = Marked K i

fun convertC :: 'a list conflicting-clause \Rightarrow 'a multiset conflicting-clause **where**
 convertC (C-Clause C) = C-Clause (mset C) |
 convertC C-True = C-True

lemma convert-CTrue[iff]:

convertC e = C-True \longleftrightarrow *e = C-True*
by (*cases e*) *auto*

lemma *convert-Propagated[elim!]*:
convert z = Propagated L C \implies ($\exists C'. z = \text{Propagated } L \ C' \wedge C = \text{mset } C'$)
by (*cases z*) *auto*

lemma *get-rev-level-map-convert*:
get-rev-level x n (map convert M) = get-rev-level x n M
by (*induction M arbitrary: n rule: marked-lit-list-induct*) *auto*

lemma *get-level-map-convert[simp]*:
get-level x (map convert M) = get-level x M
using *get-rev-level-map-convert[of x 0 rev M]* **by** (*simp add: rev-map*)

lemma *get-maximum-level-map-convert[simp]*:
get-maximum-level D (map convert M) = get-maximum-level D M
by (*induction D*)
(auto simp add: get-maximum-level-plus)

lemma *get-all-levels-of-marked-map-convert[simp]*:
get-all-levels-of-marked (map convert M) = (get-all-levels-of-marked M)
by (*induction M rule: marked-lit-list-induct*) *auto*

Conversion function

fun *toS* :: *cdcl_W-state-inv-st* \Rightarrow *nat cdcl_W-state* **where**
toS (M, N, U, k, C) = (map convert M, mset (map mset N), mset (map mset U), k, convertC C)

Definition an abstract type

typedef *cdcl_W-state-inv* = {*S*::*cdcl_W-state-inv-st. cdcl_W-all-struct-inv (toS S)*}
morphisms *rough-state-of state-of*
proof
show ($\square, \square, \square, 0, C\text{-True}$) \in {*S. cdcl_W-all-struct-inv (toS S)*}
by (*auto simp add: cdcl_W-all-struct-inv-def*)
qed

instantiation *cdcl_W-state-inv* :: *equal*

begin

definition *equal-cdcl_W-state-inv* :: *cdcl_W-state-inv* \Rightarrow *cdcl_W-state-inv* \Rightarrow *bool* **where**
equal-cdcl_W-state-inv S S' = (rough-state-of S = rough-state-of S')

instance

by *standard (simp add: rough-state-of-inject equal-cdcl_W-state-inv-def)*

end

lemma *lits-of-map-convert[simp]*: *lits-of (map convert M) = lits-of M*
by (*induction M rule: marked-lit-list-induct*) *simp-all*

lemma *undefined-lit-map-convert[iff]*:
undefined-lit (map convert M) L \longleftrightarrow *undefined-lit M L*
by (*auto simp add: Marked-Propagated-in-iff-in-lits-of*)

lemma *true-annot-map-convert[simp]*: *map convert M* \models_a *N* \longleftrightarrow *M* \models_a *N*
by (*induction M rule: marked-lit-list-induct*) (*simp-all add: true-annot-def*)

lemma *true-annots-map-convert*[simp]: *map convert M \models_{as} N \longleftrightarrow M \models_{as} N*
unfolding *true-annots-def* **by** *auto*

lemmas *propagateE*

lemma *find-first-unit-clause-some-is-propagate*:

assumes *H*: *find-first-unit-clause* (*N @ U*) *M* = *Some* (*L*, *C*)

shows *propagate* (*toS* (*M*, *N*, *U*, *k*, *C-True*)) (*toS* (*Propagated L C # M*, *N*, *U*, *k*, *C-True*))

using *assms*

by (*auto dest!*: *find-first-unit-clause-some simp add: propagate.simps*

intro!: *exI*[*of - mset C - {#L#}*])

18.3.2 Propagate

definition *do-propagate-step* **where**

do-propagate-step S =

(*case S of*

(*M*, *N*, *U*, *k*, *C-True*) \Rightarrow

(*case find-first-unit-clause* (*N @ U*) *M of*

Some (*L*, *C*) \Rightarrow (*Propagated L C # M*, *N*, *U*, *k*, *C-True*)

| *None* \Rightarrow (*M*, *N*, *U*, *k*, *C-True*))

| *S* \Rightarrow *S*)

lemma *do-propagate-step*:

do-propagate-step S $\neq S \implies$ *propagate* (*toS S*) (*toS* (*do-propagate-step S*))

apply (*cases S*, *cases conflicting S*)

using *find-first-unit-clause-some-is-propagate*[*of clauses S learned-clss S trail S - - backtrack-lvl S*]

by (*auto simp add: do-propagate-step-def split: option.splits*)

lemma *do-propagate-step-conflicting-clause*[simp]:

conflicting S $\neq C-True \implies$ *do-propagate-step S* = *S*

unfolding *do-propagate-step-def* **by** (*cases S*, *cases conflicting S*) *auto*

lemma *do-propagate-step-no-step*:

assumes *dist*: $\forall c \in \text{set } (\text{clauses } S @ \text{learned-clss } S).$ *distinct c* **and**

prop-step: *do-propagate-step S* = *S*

shows *no-step propagate* (*toS S*)

proof (*standard*, *standard*)

fix *T*

assume *propagate* (*toS S*) *T*

then obtain *M N U k C L* **where**

toSS: *toS S* = (*M*, *N*, *U*, *k*, *C-True*) **and**

T: *T* = (*Propagated L* (*C* + {*#L#*}) *# M*, *N*, *U*, *k*, *C-True*) **and**

MC: *M* \models_{as} *CNot C* **and**

undef: *undefined-lit M L* **and**

CL: *C* + {*#L#*} $\in \#$ *N* + *U*

apply - by (*cases toS S*) *auto*

let *?M* = *trail S*

let *?N* = *clauses S*

let *?U* = *learned-clss S*

let *?k* = *backtrack-lvl S*

let *?D* = *C-True*

have *S*: *S* = (*?M*, *?N*, *?U*, *?k*, *?D*)

using *toSS* **by** (*cases S*, *cases conflicting S*) *simp-all*

have *S*: *toS S* = *toS* (*?M*, *?N*, *?U*, *?k*, *?D*)

unfolding *S[symmetric]* **by** *simp*

```

have
  M: M = map convert ?M and
  N: N = mset (map mset ?N) and
  U: U = mset (map mset ?U)
  using toSS[unfolded S] by auto

obtain D where
  DCL: mset D = C + {#L#} and
  D: D ∈ set (?N @ ?U)
  using CL unfolding N U by auto
obtain C' L' where
  setD: set D = set (L' # C') and
  C': mset C' = C and
  L: L = L'
  using DCL by (metis ex-mset mset.simps(2) mset-eq-setD)
have find-first-unit-clause (?N @ ?U) ?M ≠ None
  apply (rule dist find-first-unit-clause-none[of D ?N @ ?U ?M L, OF - D ])
  using D assms(1) apply auto[1]
  using MC setD DCL M MC unfolding C'[symmetric] apply auto[1]
  using M undef apply auto[1]
  unfolding setD L by auto
then show False using prop-step S unfolding do-propagate-step-def by (cases S) auto
qed

Conflict fun find-conflict where
  find-conflict M [] = None |
  find-conflict M (N # Ns) = (if (∀ c ∈ set N. ¬c ∈ lits-of M) then Some N else find-conflict M Ns)

lemma find-conflict-Some:
  find-conflict M Ns = Some N ⇒ N ∈ set Ns ∧ M ⊨as CNot (mset N)
  by (induction Ns rule: find-conflict.induct)
  (auto split: split-if-asm)

lemma find-conflict-None:
  find-conflict M Ns = None ⇔ (∀ N ∈ set Ns. ¬M ⊨as CNot (mset N))
  by (induction Ns) auto

lemma find-conflict-None-no-conflict:
  find-conflict M (N@U) = None ⇔ no-step conflict (toS (M, N, U, k, C-True))
  by (auto simp add: find-conflict-None conflict.simps)

definition do-conflict-step where
  do-conflict-step S =
    (case S of
      (M, N, U, k, C-True) ⇒
        (case find-conflict M (N @ U) of
          Some a ⇒ (M, N, U, k, C-Clause a)
          | None ⇒ (M, N, U, k, C-True))
    | S ⇒ S)

lemma do-conflict-step:
  do-conflict-step S ≠ S ⇒ conflict (toS S) (toS (do-conflict-step S))
  apply (cases S, cases conflicting S)
  unfolding conflict.simps do-conflict-step-def

```

```

by (auto dest!: find-conflict-Some split: option.splits)

lemma do-conflict-step-no-step:
  do-conflict-step  $S = S \implies$  no-step conflict (toS  $S$ )
  apply (cases  $S$ , cases conflicting  $S$ )
  unfolding do-conflict-step-def
  using find-conflict-None-no-confl[of trail  $S$  clauses  $S$  learned-clss  $S$ 
    backtrack-lvl  $S$ ]
  by (auto split: option.splits)

lemma do-conflict-step-conflicting-clause[simp]:
  conflicting  $S \neq C\text{-True} \implies$  do-conflict-step  $S = S$ 
  unfolding do-conflict-step-def by (cases  $S$ , cases conflicting  $S$ ) auto

lemma do-conflict-step-conflicting[dest]:
  do-conflict-step  $S \neq S \implies$  conflicting (do-conflict-step  $S$ )  $\neq C\text{-True}$ 
  unfolding do-conflict-step-def by (cases  $S$ , cases conflicting  $S$ ) (auto split: option.splits)

definition do-cp-step where
  do-cp-step  $S =$ 
    (do-propagate-step o do-conflict-step)  $S$ 

lemma cp-step-is-cdclW-cp:
  assumes  $H$ : do-cp-step  $S \neq S$ 
  shows cdclW-cp (toS  $S$ ) (toS (do-cp-step  $S$ ))
proof -
  show ?thesis
  proof (cases do-conflict-step  $S \neq S$ )
    case True
    then show ?thesis
      by (auto simp add: do-conflict-step do-conflict-step-conflicting do-cp-step-def)
  next
    case False
    then have confl[simp]: do-conflict-step  $S = S$  by simp
    show ?thesis
      proof (cases do-propagate-step  $S = S$ )
        case True
        then show ?thesis
          using  $H$  by (simp add: do-cp-step-def)
      next
        case False
        let ?S = toS  $S$ 
        let ?T = toS (do-propagate-step  $S$ )
        let ?U = toS (do-conflict-step (do-propagate-step  $S$ ))
        have propa: propagate (toS  $S$ ) ?T using False do-propagate-step by blast
        moreover have ns: no-step conflict (toS  $S$ ) using confl do-conflict-step-no-step by blast
        ultimately show ?thesis
          using cdclW-cp.intros(2)[of ?S ?T] confl unfolding do-cp-step-def by auto
      qed
    qed
  qed
qed

lemma do-cp-step-eq-no-prop-no-confl:
  do-cp-step  $S = S \implies$  do-conflict-step  $S = S \wedge$  do-propagate-step  $S = S$ 
  by (cases  $S$ , cases conflicting  $S$ )

```

(auto simp add: do-conflict-step-def do-propagate-step-def do-cp-step-def split: option.splits)

lemma no-cdcl_W-cp-iff-no-propagate-no-conflict:
 no-step cdcl_W-cp $S \longleftrightarrow$ no-step propagate $S \wedge$ no-step conflict S
 by (auto simp: cdcl_W-cp.simps)

lemma do-cp-step-eq-no-step:
 assumes H : do-cp-step $S = S$ and $\forall c \in \text{set } (\text{clauses } S @ \text{learned-clss } S)$. distinct c
 shows no-step cdcl_W-cp (toS S)
 unfolding no-cdcl_W-cp-iff-no-propagate-no-conflict
 using assms apply (cases S , cases conflicting S)
 using do-propagate-step-no-step[of S]
 by (auto dest!: do-cp-step-eq-no-prop-no-conf[simplified] do-conflict-step-no-step
 split: option.splits)

lemma cdcl_W-cp-cdcl_W-st: cdcl_W-cp $S S' \implies$ cdcl_W^{**} $S S'$
 by (simp add: cdcl_W-cp-tranclp-cdcl_W tranclp-into-rtranclp)

lemma cdcl_W-cp-wf-all-inv: wf $\{(S', S::'v::\text{linorder } \text{cdcl}_W\text{-state}). \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-cp } S S'\}$

(is wf ?R)

proof (rule wf-bounded-measure[of - λS . card (atms-of-msu (clauses S))+1
 λS . length (trail S) + (if conflicting $S = C\text{-True}$ then 0 else 1)], goal-cases)

case (1 $S S'$)

then have cdcl_W-all-struct-inv S and cdcl_W-cp $S S'$ by auto

moreover then have cdcl_W-all-struct-inv S'

using rtranclp-cdcl_W-all-struct-inv-inv cdcl_W-cp-cdcl_W-st by blast

ultimately show ?case

by (auto simp add: cdcl_W-cp.simps elim!: conflictE propagateE
 dest: length-model-le-vars-all-inv)

qed

lemma cdcl_W-all-struct-inv-rough-state[simp]: cdcl_W-all-struct-inv (toS (rough-state-of S))
 using rough-state-of by auto

lemma [simp]: cdcl_W-all-struct-inv (toS S) \implies rough-state-of (state-of S) = S
 by (simp add: state-of-inverse)

lemma rough-state-of-state-of-do-cp-step[simp]:
 rough-state-of (state-of (do-cp-step (rough-state-of S))) = do-cp-step (rough-state-of S)

proof –

have cdcl_W-all-struct-inv (toS (do-cp-step (rough-state-of S)))

apply (cases do-cp-step (rough-state-of S) = (rough-state-of S))

apply simp

using cp-step-is-cdcl_W-cp[of rough-state-of S]

cdcl_W-all-struct-inv-rough-state[of S] cdcl_W-cp-cdcl_W-st rtranclp-cdcl_W-all-struct-inv-inv by blast

then show ?thesis by auto

qed

Skip fun do-skip-step :: cdcl_W-state-inv-st \Rightarrow cdcl_W-state-inv-st **where**

do-skip-step (Propagated $L C \# Ls, N, U, k, C\text{-Clause } D$) =

(if $-L \notin \text{set } D \wedge D \neq []$

then ($Ls, N, U, k, C\text{-Clause } D$)

else (Propagated $L C \# Ls, N, U, k, C\text{-Clause } D$)) |

do-skip-step $S = S$

lemma *do-skip-step*:

do-skip-step $S \neq S \implies \text{skip } (\text{toS } S) (\text{toS } (\text{do-skip-step } S))$
apply (*induction* S *rule*: *do-skip-step.induct*)
by (*auto simp add*: *skip.simps*)

lemma *do-skip-step-no*:

do-skip-step $S = S \implies \text{no-step skip } (\text{toS } S)$
by (*induction* S *rule*: *do-skip-step.induct*)
(*auto simp add*: *other split*: *split-if-asm*)

lemma *do-skip-step-trail-is-C-True*[*iff*]:

do-skip-step $S = (a, b, c, d, C\text{-True}) \longleftrightarrow S = (a, b, c, d, C\text{-True})$
by (*cases* S *rule*: *do-skip-step.cases*) *auto*

Resolve fun *maximum-level-code*:: '*a literal list* \Rightarrow ('*a*, *nat*, '*a literal list*) *marked-lit list* \Rightarrow *nat* **where**

maximum-level-code [] = 0 |

maximum-level-code ($L \# Ls$) $M = \max (\text{get-level } L \ M) (\text{maximum-level-code } Ls \ M)$

lemma *maximum-level-code-eq-get-maximum-level*[*code, simp*]:

maximum-level-code $D \ M = \text{get-maximum-level } (\text{mset } D) \ M$
by (*induction* D) (*auto simp add*: *get-maximum-level-plus*)

fun *do-resolve-step* :: *cdcl_W-state-inv-st* \Rightarrow *cdcl_W-state-inv-st* **where**

do-resolve-step (*Propagated* $L \ C \ \# \ Ls, N, U, k, C\text{-Clause } D$) =

(*if* $-L \in \text{set } D \wedge (\text{maximum-level-code } (\text{remove1 } (-L) \ D) (\text{Propagated } L \ C \ \# \ Ls) = k \vee k = 0)$
then ($Ls, N, U, k, C\text{-Clause } (\text{remdups } (\text{remove1 } L \ C \ @ \ \text{remove1 } (-L) \ D))$)
else (*Propagated* $L \ C \ \# \ Ls, N, U, k, C\text{-Clause } D$)) |

do-resolve-step $S = S$

lemma *distinct-mset-remdups-union-mset*:

assumes *distinct-mset* A **and** *distinct-mset* B

shows $A \ \# \cup B = \text{remdups-mset } (A + B)$

using *assms* **unfolding** *remdups-mset-def* **apply** (*auto simp*: *multiset-eq-iff max-def*)

apply (*metis* *Un-iff count-mset-set*(1) *count-mset-set*(3) *distinct-mset-set-mset-ident*
finite-UnI finite-set-mset mem-set-mset-iff not-le)

by (*simp add*: *distinct-mset-def*)

lemma *do-resolve-step*:

cdcl_W-all-struct-inv (*toS* S) $\implies \text{do-resolve-step } S \neq S$

$\implies \text{resolve } (\text{toS } S) (\text{toS } (\text{do-resolve-step } S))$

proof (*induction* S *rule*: *do-resolve-step.induct*)

case ($1 \ L \ C \ M \ N \ U \ k \ D$)

moreover

{ **assume** [*simp*]: $k = 0$

have *get-all-levels-of-marked* (*Propagated* $L \ C \ \# \ M$) = []

using $1(1)$ **unfolding** *cdcl_W-all-struct-inv-def cdcl_W-M-level-inv-def* **by** *simp*

then have $H: \bigwedge L'. \text{get-level } L' (\text{Propagated } L \ C \ \# \ M) = 0$

by (*metis* (*no-types, hide-lams*) *Un-insert-left empty-iff get-all-levels-of-marked.simps*(3)
get-level-in-levels-of-marked insert-iff list.set(1) *sup-bot.left-neutral*)

} **note** $H = \text{this}$

ultimately have

$- L \in \text{set } D$ **and**

$M: \text{maximum-level-code } (\text{remove1 } (-L) \ D) (\text{Propagated } L \ C \ \# \ M) = k$


```

    by (cases mset D - {#- L#} = {#},
        auto dest!: get-maximum-level-exists-lit-of-max-level[of - Propagated L C # M]
        split: split-if-asm simp add: H)+
  have every-mark-is-a-conflict (toS (Propagated L C # M, N, U, k, C-Clause D))
    using 1(1) unfolding cdclW-all-struct-inv-def cdclW-conflicting-def by fast
  then have L ∈ set C by fastforce
  then obtain C' where C: mset C = C' + {#L#}
    by (metis add.commute in-multiset-in-set insert-DiffM)
  obtain D' where D: mset D = D' + {#-L#}
    using ⟨- L ∈ set D⟩ by (metis add.commute in-multiset-in-set insert-DiffM)
  have D'L: D' + {#- L#} - {#-L#} = D' by (auto simp add: multiset-eq-iff)

  have CL: mset C - {#L#} + {#L#} = mset C using ⟨L ∈ set C⟩ by (auto simp add: multiset-eq-iff)
  have
    resolve
      (map convert (Propagated L C # M), mset '# mset N, mset '# mset U, k, C-Clause (mset D))
      (map convert M, mset '# mset N, mset '# mset U, k,
        C-Clause (((mset D - {#-L#}) # ∪ (mset C - {#L#}))))
    unfolding resolve.simps
    apply (simp add: C D)
    using M[simplified] unfolding maximum-level-code-eq-get-maximum-level C[symmetric] CL
    by (metis D D'L convert.simps(1) get-maximum-level-map-convert list.simps(9))
  moreover have
    (map convert (Propagated L C # M), mset '# mset N, mset '# mset U, k, C-Clause (mset D))
    = toS (Propagated L C # M, N, U, k, C-Clause D)
    by auto
  moreover
    have distinct-mset (mset C) and distinct-mset (mset D)
      using ⟨cdclW-all-struct-inv (toS (Propagated L C # M, N, U, k, C-Clause D))⟩
      unfolding cdclW-all-struct-inv-def distinct-cdclW-state-def
      by auto
    then have (mset C - {#L#}) # ∪ (mset D - {#- L#}) =
      remdups-mset (mset C - {#L#} + (mset D - {#- L#}))
      apply -
      apply (rule distinct-mset-remdups-union-mset)
      by auto
    then have (map convert M, mset '# mset N, mset '# mset U, k,
      C-Clause (((mset D - {#- L#}) # ∪ (mset C - {#L#}))))
    = toS (do-resolve-step (Propagated L C # M, N, U, k, C-Clause D))
      using ⟨- L ∈ set D⟩ M by (auto simp:ac-simps)
    ultimately show ?case
      by simp
qed auto

lemma do-resolve-step-no:
  do-resolve-step S = S ⇒ no-step resolve (toS S)
apply (cases S; cases hd (trail S); cases conflicting S)
by (auto
  elim!: resolveE split: split-if-asm
  dest!: union-single-eq-member
  simp del: in-multiset-in-set get-maximum-level-map-convert
  simp add: in-multiset-in-set[symmetric] get-maximum-level-map-convert[symmetric])

lemma rough-state-of-state-of-resolve[simp]:

```

cdcl_W-all-struct-inv (toS S) \implies *rough-state-of* (state-of (do-resolve-step S)) = do-resolve-step S
apply (rule state-of-inverse)
by (smt CollectI bj *cdcl_W-all-struct-inv-inv* do-resolve-step other resolve)

lemma *do-resolve-step-trail-is-C-True*[iff]:
do-resolve-step S = (a, b, c, d, C-True) \longleftrightarrow S = (a, b, c, d, C-True)
by (cases S rule: do-resolve-step.cases)
auto

Backjumping **fun** *find-level-decomp* **where**

find-level-decomp M [] D k = None |
find-level-decomp M (L # Ls) D k =
(case (get-level L M, maximum-level-code (D @ Ls) M) of
(i, j) \Rightarrow if i = k \wedge j < i then Some (L, j) else *find-level-decomp* M Ls (L#D) k
)

lemma *find-level-decomp-some*:
assumes *find-level-decomp* M Ls D k = Some (L, j)
shows L \in set Ls \wedge get-maximum-level (mset (remove1 L (Ls @ D))) M = j \wedge get-level L M = k
using *assms*
apply (induction Ls arbitrary: D)
apply *simp*
apply (auto split: split-if-asm simp add: ac-simps)
apply (smt ab-semigroup-add-class.add-ac(1) add.commute diff-union-swap mset.simps(2))
apply (smt add.commute add.left-commute diff-union-cancelL mset.simps(2))
apply (smt add.commute add.left-commute diff-union-swap mset.simps(2))
done

lemma *find-level-decomp-none*:
assumes *find-level-decomp* M Ls E k = None **and** mset (L#D) = mset (Ls @ E)
shows \neg (L \in set Ls \wedge get-maximum-level (mset D) M < k \wedge k = get-level L M)
using *assms*
proof (induction Ls arbitrary: E L D)
case Nil
then show ?case **by** *simp*
next
case (Cons L' Ls) **note** IH = *this*(1) **and** *find-none* = *this*(2) **and** LD = *this*(3)
have mset D + {#L'#} = mset E + (mset Ls + {#L'#}) \implies mset D = mset E + mset Ls
by (metis add-right-imp-eq union-assoc)
then show ?case
using *find-none* IH[of L' # E L D] LD **by** (auto simp add: ac-simps split: split-if-asm)
qed

fun *bt-cut* **where**

bt-cut i (Propagated - - # Ls) = *bt-cut* i Ls |
bt-cut i (Marked K k # Ls) = (if k = Suc i then Some (Marked K k # Ls) else *bt-cut* i Ls) |
bt-cut i [] = None

lemma *bt-cut-some-decomp*:
bt-cut i M = Some M' $\implies \exists$ K M2 M1. M = M2 @ M' \wedge M' = Marked K (i+1) # M1
by (induction i M rule: *bt-cut.induct*) (auto split: split-if-asm)

lemma *bt-cut-not-none*: M = M2 @ Marked K (Suc i) # M' \implies *bt-cut* i M \neq None
by (induction M2 arbitrary: M rule: marked-lit-list-induct) auto

lemma *get-all-marked-decomposition-ex*:

$\exists N. (\text{Marked } K (\text{Suc } i) \# M', N) \in \text{set } (\text{get-all-marked-decomposition } (M2 @ \text{Marked } K (\text{Suc } i) \# M'))$

apply (*induction* $M2$ *rule*: *marked-lit-list-induct*)

apply *auto*[2]

by (*case-tac* *get-all-marked-decomposition* ($xs @ \text{Marked } K (\text{Suc } i) \# M'$) *auto*)

lemma *bt-cut-in-get-all-marked-decomposition*:

$\text{bt-cut } i \ M = \text{Some } M' \implies \exists M2. (M', M2) \in \text{set } (\text{get-all-marked-decomposition } M)$

by (*auto* *dest!*: *bt-cut-some-decomp simp add: get-all-marked-decomposition-ex*)

fun *do-backtrack-step* **where**

do-backtrack-step ($M, N, U, k, C\text{-Clause } D$) =

(*case* *find-level-decomp* $M \ D \ [] \ k \ \text{of}$

None $\Rightarrow (M, N, U, k, C\text{-Clause } D)$

| *Some* (L, j) \Rightarrow

(*case* *bt-cut* $j \ M \ \text{of}$

Some ($\text{Marked } - \ - \# Ls$) $\Rightarrow (\text{Propagated } L \ D \# Ls, N, D \# U, j, C\text{-True})$

| $- \Rightarrow (M, N, U, k, C\text{-Clause } D)$)

) |

do-backtrack-step $S = S$

lemma *get-all-marked-decomposition-map-convert*:

(*get-all-marked-decomposition* (*map* *convert* M)) =

map ($\lambda(a, b). (\text{map } \text{convert } a, \text{map } \text{convert } b))$ (*get-all-marked-decomposition* M)

apply (*induction* M *rule*: *marked-lit-list-induct*)

apply *simp*

by (*case-tac* *get-all-marked-decomposition* xs , *auto*) $+$

lemma *do-backtrack-step*:

assumes *db*: *do-backtrack-step* $S \neq S$

and *inv*: *cdcl_W-all-struct-inv* (*toS* S)

shows *backtrack* (*toS* S) (*toS* (*do-backtrack-step* S))

proof (*cases* S , *cases* *conflicting* S , *goal-cases*)

case ($1 \ M \ N \ U \ k \ E$)

then show *?case* **using** *db* **by** *auto*

next

case ($2 \ M \ N \ U \ k \ E \ C$) **note** $S = \text{this}(1)$ **and** *confl* = *this*(2)

have $E: E = C\text{-Clause } C$ **using** $S \ \text{confl}$ **by** *auto*

obtain $L \ j$ **where** *fd*: *find-level-decomp* $M \ C \ [] \ k = \text{Some } (L, j)$

using *db* **unfolding** $S \ E$ **by** (*cases* C) (*auto* *split*: *split-if-asm option.splits*)

have $L \in \text{set } C$ **and** *get-maximum-level* (*mset* (*remove1* $L \ C$)) $M = j$ **and**

levL: *get-level* $L \ M = k$

using *find-level-decomp-some*[*OF* *fd*] **by** *auto*

obtain C' **where** $C: \text{mset } C = \text{mset } C' + \{\#L\# \}$

using ($L \in \text{set } C$) **by** (*metis* *add.commute ex-mset in-multiset-in-set insert-DiffM*)

obtain M_2 **where** $M_2: \text{bt-cut } j \ M = \text{Some } M_2$

using *db* *fd* **unfolding** $S \ E$ **by** (*auto* *split*: *option.splits*)

obtain $M1 \ K$ **where** $M1: M_2 = \text{Marked } K (\text{Suc } j) \# M1$

using *bt-cut-some-decomp*[*OF* M_2] **by** (*cases* M_2) *auto*

obtain c **where** $c: M = c @ \text{Marked } K (\text{Suc } j) \# M1$

using *bt-cut-in-get-all-marked-decomposition*[*OF* M_2]

unfolding $M1$ **by** *fastforce*

have *get-all-levels-of-marked* (*map* *convert* M) = *rev* [$1..<\text{Suc } k$]

```

    using inv unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def S by auto
  from arg-cong[OF this, of  $\lambda a. \text{Suc } j \in \text{set } a$ ] have  $j \leq k$  unfolding c by auto
  have max-l-j: maximum-level-code  $C' M = j$ 
    using db fd  $M_2 C$  unfolding S E by (auto
      split: option.splits list.splits marked-lit.splits
      dest!: find-level-decomp-some)[1]
  have get-maximum-level (mset C)  $M \geq k$ 
    using  $\langle L \in \text{set } C \rangle$  get-maximum-level-ge-get-level levL by blast
  moreover have get-maximum-level (mset C)  $M \leq k$ 
    using get-maximum-level-exists-lit-of-max-level[of mset C M] inv
      cdclW-M-level-inv-get-level-le-backtrack-lvl[of toS S]
    unfolding C cdclW-all-struct-inv-def S
    by auto metis+
  ultimately have get-maximum-level (mset C)  $M = k$  by auto

  obtain M2 where  $M2: (M_2, M2) \in \text{set } (\text{get-all-marked-decomposition } M)$ 
    using bt-cut-in-get-all-marked-decomposition[OF  $M_2$ ] by metis
  have H: (cdclW.reduce-trail-to (map convert M1)
    (add-learned-cls (mset  $C' + \{\#L\# \}$ )
      (map convert M, mset (map mset N), mset (map mset U), j, C-True))) =
    (map convert M1, mset (map mset N),  $\{\#mset C' + \{\#L\#\}\# \} + \text{mset } (\text{map mset } U), j, C-True)$ 
    apply (subst state-conv[of cdclW.reduce-trail-to - -])
    using M2 unfolding M1 by auto
  have
    backtrack
      (map convert M, mset  $\# \text{ mset } N$ , mset  $\# \text{ mset } U$ , k, C-Clause (mset C))
      (Propagated L (mset C)  $\# \text{ map convert } M1$ , mset  $\# \text{ mset } N$ , mset  $\# \text{ mset } U + \{\#mset C\# \}$ ,
    j,
      C-True)
  apply (rule backtrack-rule)
    unfolding C apply simp
    using Set.imageI[of  $(M_2, M2)$  set (get-all-marked-decomposition M)
       $(\lambda(a, b). (\text{map convert } a, \text{map convert } b))$ ] M2
    apply (auto simp: get-all-marked-decomposition-map-convert M1)[1]
    using max-l-j levL  $\langle j \leq k \rangle$  apply (simp add: get-maximum-level-plus)
    using C  $\langle \text{get-maximum-level (mset C) } M = k \rangle$  levL apply auto[1]
    using max-l-j apply simp
  apply (cases cdclW.reduce-trail-to (map convert M1)
    (add-learned-cls (mset  $C' + \{\#L\# \}$ )
      (map convert M, mset (map mset N), mset (map mset U), j, C-True)))
    using M2 M1 H by (auto simp: ac-simps)
  then show ?case
    using  $M_2$  fd unfolding S E M1 by auto
  obtain M2 where  $(M_2, M2) \in \text{set } (\text{get-all-marked-decomposition } M)$ 
    using bt-cut-in-get-all-marked-decomposition[OF  $M_2$ ] by metis
qed

lemma do-backtrack-step-no:
  assumes db: do-backtrack-step  $S = S$ 
  and inv: cdclW-all-struct-inv (toS S)
  shows no-step backtrack (toS S)
proof (rule ccontr, cases S, cases conflicting S, goal-cases)
  case 1
  then show ?case using db by (auto split: option.splits)
next

```

```

case (2 M N U k E C) note bt = this(1) and S = this(2) and confl = this(3)
obtain D L K b z M1 j where
  levL: get-level L M = get-maximum-level (D + {#L#}) M and
  k: k = get-maximum-level (D + {#L#}) M and
  j: j = get-maximum-level D M and
  CE: convertC E = C-Clause (D + {#L#}) and
  decomp: (z # M1, b) ∈ set (get-all-marked-decomposition M) and
  z: Marked K (Suc j) = convert z using bt unfolding S
    by (auto split: option.splits elim!: backtrackE
      simp: get-all-marked-decomposition-map-convert)
have z: z = Marked K (Suc j) using z by (cases z) auto
obtain c where c: M = c @ b @ Marked K (Suc j) # M1
  using decomp unfolding z by blast
have get-all-levels-of-marked (map convert M) = rev [1..<Suc k]
  using inv unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def S by auto
from arg-cong[OF this, of λa. Suc j ∈ set a] have k > j unfolding c by auto
obtain C D' where
  E: E = C-Clause C and
  C: mset C = mset (L # D')
  using CE apply (cases E)
    apply simp
  by (metis conflicting-clause.inject convertC.simps(1) ex-mset mset.simps(2))
have D'D: mset D' = D
  using C CE E by auto
have find-level-decomp M C [] k ≠ None
  apply rule
  apply (drule find-level-decomp-none[of - - - L D'])
  using C ⟨k > j⟩ mset-eq-setD unfolding k[symmetric] D'D j[symmetric] levL by fastforce+
then obtain L' j' where fd-some: find-level-decomp M C [] k = Some (L', j')
  by (cases find-level-decomp M C [] k) auto
have L': L' = L
  proof (rule ccontr)
    assume ¬ ?thesis
    then have L' ∈ # D
      by (metis C D'D fd-some find-level-decomp-some in-multiset-in-set insert-iff list.simps(15))
    then have get-level L' M ≤ get-maximum-level D M
      using get-maximum-level-ge-get-level by blast
    then show False using ⟨k > j⟩ j find-level-decomp-some[OF fd-some] by auto
  qed
then have j': j' = j using find-level-decomp-some[OF fd-some] j C D'D by auto

have btc-none: bt-cut j M ≠ None
  apply (rule bt-cut-not-none[of M - @ -])
  using c by simp
show ?case using db unfolding S E
  by (auto split: option.splits list.splits marked-lit.splits
    simp add: fd-some L' j' btc-none
    dest: bt-cut-some-decomp)
qed

```

```

lemma rough-state-of-state-of-backtrack[simp]:
  assumes inv: cdclW-all-struct-inv (toS S)
  shows rough-state-of (state-of (do-backtrack-step S)) = do-backtrack-step S
proof (rule state-of-inverse)
  have f2: backtrack (toS S) (toS (do-backtrack-step S)) ∨ do-backtrack-step S = S

```

```

    using do-backtrack-step inv by blast
  have  $\bigwedge p. \neg \text{cdcl}_W\text{-o } (toS\ S) \ p \vee \text{cdcl}_W\text{-all-struct-inv } p$ 
    using inv cdclW-all-struct-inv-inv other by blast
  then have do-backtrack-step  $S = S \vee \text{cdcl}_W\text{-all-struct-inv } (toS\ (do\text{-backtrack-step } S))$ 
    using f2 by blast
  then show do-backtrack-step  $S \in \{S. \text{cdcl}_W\text{-all-struct-inv } (toS\ S)\}$ 
    using inv by fastforce
qed

```

Decide fun do-decide-step where

```

do-decide-step (M, N, U, k, C-True) =
  (case find-first-unused-var N (lits-of M) of
    None  $\Rightarrow$  (M, N, U, k, C-True)
  | Some L  $\Rightarrow$  (Marked L (Suc k) # M, N, U, k+1, C-True)) |
do-decide-step S = S

```

lemma do-decide-step:

```

do-decide-step  $S \neq S \implies \text{decide } (toS\ S) \ (toS\ (do\text{-decide-step } S))$ 
apply (cases S, cases conflicting S)
defer
apply (auto split: option.splits simp add: decide.simps Marked-Propagated-in-iff-in-lits-of
  dest: find-first-unused-var-undefined find-first-unused-var-Some
  intro: atms-of-atms-of-ms-mono)[1]

```

proof –

```

fix a b c d e
{
  fix a :: (nat, nat, nat literal list) marked-lit list and
    b :: nat literal list list and c :: nat literal list list and
    d :: nat and x2 :: nat literal and m :: nat literal list
  assume a1:  $m \in \text{set } b$ 
  assume x2  $\in \text{set } m$ 
  then have f2:  $\text{atm-of } x2 \in \text{atms-of } (\text{mset } m)$ 
    by simp
  have  $\bigwedge f. (f\ m :: \text{nat literal multiset}) \in f\ ' \text{set } b$ 
    using a1 by blast
  then have  $\bigwedge f. (\text{atms-of } (f\ m) :: \text{nat set}) \subseteq \text{atms-of-ms } (f\ ' \text{set } b)$ 
    using atms-of-atms-of-ms-mono by blast
  then have  $\bigwedge n f. (n :: \text{nat}) \in \text{atms-of-ms } (f\ ' \text{set } b) \vee n \notin \text{atms-of } (f\ m)$ 
    by (meson contra-subsetD)
  then have  $\text{atm-of } x2 \in \text{atms-of-ms } (\text{mset } ' \text{set } b)$ 
    using f2 by blast
} note H = this
assume do-decide-step  $S \neq S$  and
  S = (a, b, c, d, e) and
  conflicting S = C-True
then show  $\text{decide } (toS\ S) \ (toS\ (do\text{-decide-step } S))$ 

```

```

  apply (auto split: option.splits simp add: decide.simps Marked-Propagated-in-iff-in-lits-of
    dest!: find-first-unused-var-Some dest: H)
  by (meson atm-of-in-atm-of-set-in-uminus contra-subsetD rev-image-eqI)+

```

qed

lemma do-decide-step-no:

```

do-decide-step  $S = S \implies \text{no-step decide } (toS\ S)$ 

```

```

apply (cases  $S$ , cases conflicting  $S$ )
apply (auto
  simp add: atms-of-ms-mset-unfold atm-of-eq-atm-of Marked-Propagated-in-iff-in-lits-of
  split: option.splits
  elim!: decideE)
apply (meson atm-of-in-atm-of-set-in-uminus image-subset-iff)
apply (meson atm-of-in-atm-of-set-in-uminus image-subset-iff)
done

```

```

lemma rough-state-of-state-of-do-decide-step[simp]:
   $cdcl_W\text{-all-struct-inv } (toS\ S) \implies \text{rough-state-of } (state\text{-of } (do\text{-decide-step } S)) = do\text{-decide-step } S$ 
apply (subst state-of-inverse)
apply (smt  $cdcl_W\text{-all-struct-inv-inv decide do-decide-step mem-Collect-eq other}$ )
apply simp
done

```

```

lemma rough-state-of-state-of-do-skip-step[simp]:
   $cdcl_W\text{-all-struct-inv } (toS\ S) \implies \text{rough-state-of } (state\text{-of } (do\text{-skip-step } S)) = do\text{-skip-step } S$ 
apply (subst state-of-inverse)
apply (smt  $cdcl_W\text{-all-struct-inv-inv skip do-skip-step mem-Collect-eq other bj}$ )
apply simp
done

```

18.3.3 Code generation

Type definition There are two invariants: one while applying conflict and propagate and one for the other rules

```

declare rough-state-of-inverse[simp add]
definition Con where
  Con  $xs = state\text{-of } (if\ cdcl_W\text{-all-struct-inv } (toS\ (fst\ xs, snd\ xs))\ then\ xs$ 
  else  $([], [], [], 0, C\text{-True}))$ 

```

```

lemma [code abstype]:
  Con (rough-state-of  $S$ ) =  $S$ 
using rough-state-of[of  $S$ ] unfolding Con-def by (simp add: rough-state-of-inverse)

```

```

definition do-cp-step' where
  do-cp-step'  $S = state\text{-of } (do\text{-cp-step } (rough\text{-state-of } S))$ 

```

```

typedef  $cdcl_W\text{-state-inv-from-init-state} = \{S::cdcl_W\text{-state-inv-st. } cdcl_W\text{-all-struct-inv } (toS\ S)$ 
   $\wedge cdcl_W\text{-stgy}^{**} (S0\text{-}cdcl_W\ (clauses\ (toS\ S))) (toS\ S)\}$ 
morphisms rough-state-from-init-state-of state-from-init-state-of
proof
  show  $([], [], [], 0, C\text{-True}) \in \{S. cdcl_W\text{-all-struct-inv } (toS\ S)$ 
   $\wedge cdcl_W\text{-stgy}^{**} (S0\text{-}cdcl_W\ (clauses\ (toS\ S))) (toS\ S)\}$ 
  by (auto simp add:  $cdcl_W\text{-all-struct-inv-def}$ )
qed

```

```

instantiation  $cdcl_W\text{-state-inv-from-init-state} :: equal$ 
begin

```

```

definition equal- $cdcl_W\text{-state-inv-from-init-state} :: cdcl_W\text{-state-inv-from-init-state} \Rightarrow$ 
   $cdcl_W\text{-state-inv-from-init-state} \Rightarrow bool$  where
  equal- $cdcl_W\text{-state-inv-from-init-state } S\ S' \longleftrightarrow$ 
   $(rough\text{-state-from-init-state-of } S = rough\text{-state-from-init-state-of } S')$ 

```

instance

by *standard* (*simp add: rough-state-from-init-state-of-inject*
equal-cdcl_W-state-inv-from-init-state-def)

end

definition *ConI* **where**

ConI S = state-from-init-state-of (*if cdcl_W-all-struct-inv* (*toS* (*fst S*, *snd S*))
 \wedge *cdcl_W-stgy*** (*S0-cdcl_W* (*clauses* (*toS S*))) (*toS S*) *then S else* (\square , \square , \square , \emptyset , *C-True*))

lemma [*code abstype*]:

ConI (*rough-state-from-init-state-of S*) = *S*

using *rough-state-from-init-state-of*[*of S*] **unfolding** *ConI-def* **by** (*simp add: rough-state-from-init-state-of-inverse*)

definition *id-of-I-to::* *cdcl_W-state-inv-from-init-state* \Rightarrow *cdcl_W-state-inv* **where**

id-of-I-to S = state-of (*rough-state-from-init-state-of S*)

lemma [*code abstract*]:

rough-state-of (*id-of-I-to S*) = *rough-state-from-init-state-of S*

unfolding *id-of-I-to-def* **using** *rough-state-from-init-state-of* **by** *auto*

Conflict and Propagate **function** *do-full1-cp-step :: cdcl_W-state-inv* \Rightarrow *cdcl_W-state-inv* **where**

do-full1-cp-step S =

(*let S' = do-cp-step' S in*

if S = S' then S else do-full1-cp-step S')

by *auto*

termination

proof (*relation* $\{(T', T). (rough-state-of T', rough-state-of T) \in \{(S', S).$

$(toS S', toS S) \in \{(S', S). cdcl_W-all-struct-inv S \wedge cdcl_W-cp S S'\}\}$, *goal-cases*)

case *1*

show *?case*

using *wf-if-measure-f*[*OF wf-if-measure-f*[*OF cdcl_W-cp-wf-all-inv, of toS*], *of rough-state-of*] .

next

case ($\exists S' S$)

then show *?case*

unfolding *do-cp-step'-def*

apply *simp*

by (*metis cp-step-is-cdcl_W-cp rough-state-of-inverse*)

qed

lemma *do-full1-cp-step-fix-point-of-do-full1-cp-step:*

do-cp-step(*rough-state-of* (*do-full1-cp-step S*)) = (*rough-state-of* (*do-full1-cp-step S*))

by (*rule do-full1-cp-step.induct*[*of* $\lambda S. do-cp-step(rough-state-of (do-full1-cp-step S))$

= (*rough-state-of* (*do-full1-cp-step S*))])

(*metis* (*full-types*) *do-full1-cp-step.elims rough-state-of-state-of-do-cp-step do-cp-step'-def*)

lemma *in-clauses-rough-state-of-is-distinct:*

$c \in set (clauses (rough-state-of S) @ learned-clss (rough-state-of S)) \implies distinct c$

apply (*cases rough-state-of S*)

using *rough-state-of*[*of S*] **by** (*auto simp add: distinct-mset-set-distinct cdcl_W-all-struct-inv-def*
distinct-cdcl_W-state-def)

lemma *do-full1-cp-step-full:*

full cdcl_W-cp (*toS* (*rough-state-of S*))

(*toS* (*rough-state-of* (*do-full1-cp-step S*)))

unfolding *full-def* **apply** *standard*

apply (*induction* S *rule*: *do-full1-cp-step.induct*)
apply (*smt* *cp-step-is-cdcl_W-cp* *do-cp-step'-def* *do-full1-cp-step.simps*
rough-state-of-state-of-do-cp-step *rtranclp.rtrancl-refl* *rtranclp-into-tranclp2*
tranclp-into-rtranclp)

apply (*rule* *do-cp-step-eq-no-step*[*OF* *do-full1-cp-step-fix-point-of-do-full1-cp-step*[*of* S]])
using *in-clauses-rough-state-of-is-distinct* **unfolding** *do-cp-step'-def* **by** *blast*

lemma [*code abstract*]:
rough-state-of (*do-cp-step'* S) = *do-cp-step* (*rough-state-of* S)
unfolding *do-cp-step'-def* **by** *auto*

The other rules **fun** *do-other-step* **where**

do-other-step S =
 (*let* T = *do-skip-step* S *in*
 if $T \neq S$
 then T
 else
 (*let* U = *do-resolve-step* T *in*
 if $U \neq T$
 then U *else*
 (*let* V = *do-backtrack-step* U *in*
 if $V \neq U$ *then* V *else* *do-decide-step* V)))

lemma *do-other-step*:
assumes *inv*: *cdcl_W-all-struct-inv* (*toS* S) **and**
st: *do-other-step* $S \neq S$
shows *cdcl_W-o* (*toS* S) (*toS* (*do-other-step* S))
using *st inv* **by** (*auto split: split-if-asm*
simp add: Let-def
intro: do-skip-step do-resolve-step do-backtrack-step do-decide-step)

lemma *do-other-step-no*:
assumes *inv*: *cdcl_W-all-struct-inv* (*toS* S) **and**
st: *do-other-step* $S = S$
shows *no-step cdcl_W-o* (*toS* S)
using *st inv* **by** (*auto split: split-if-asm elim: cdcl_W-bjE*
simp add: Let-def cdcl_W-bj.simps elim!: cdcl_W-o.cases
dest!: do-skip-step-no do-resolve-step-no do-backtrack-step-no do-decide-step-no)

lemma *rough-state-of-state-of-do-other-step*[*simp*]:
rough-state-of (*state-of* (*do-other-step* (*rough-state-of* S))) = *do-other-step* (*rough-state-of* S)
proof (*cases* *do-other-step* (*rough-state-of* S) = *rough-state-of* S)
 case True
 then show *?thesis* **by** *simp*
next
 case False
 have *cdcl_W-o* (*toS* (*rough-state-of* S)) (*toS* (*do-other-step* (*rough-state-of* S)))
 by (*metis* *False cdcl_W-all-struct-inv-rough-state do-other-step*[*of* *rough-state-of* S])
 then have *cdcl_W-all-struct-inv* (*toS* (*do-other-step* (*rough-state-of* S)))
 using *cdcl_W-all-struct-inv-inv cdcl_W-all-struct-inv-rough-state other* **by** *blast*
 then show *?thesis*
 by (*simp add: CollectI state-of-inverse*)
qed

definition *do-other-step'* **where**

do-other-step' $S =$
state-of (*do-other-step* (*rough-state-of* S))

lemma *rough-state-of-do-other-step'* [code abstract]:

rough-state-of (*do-other-step'* S) = *do-other-step* (*rough-state-of* S)

apply (*cases* *do-other-step* (*rough-state-of* S) = *rough-state-of* S)

unfolding *do-other-step'-def* **apply** *simp*

using *do-other-step* [of *rough-state-of* S] **by** (*smt* *cdcl_W-all-struct-inv-inv*
cdcl_W-all-struct-inv-rough-state mem-Collect-eq other state-of-inverse)

definition *do-cdcl_W-stgy-step* **where**

do-cdcl_W-stgy-step $S =$
 (*let* $T = \text{do-full1-cp-step } S$ *in*
 if $T \neq S$
 then T
 else
 (*let* $U = (\text{do-other-step}' T)$ *in*
 (*do-full1-cp-step* U)))

definition *do-cdcl_W-stgy-step'* **where**

do-cdcl_W-stgy-step' $S = \text{state-from-init-state-of } (\text{rough-state-of } (\text{do-cdcl}_W\text{-stgy-step } (\text{id-of-I-to } S)))$

lemma *toS-do-full1-cp-step-not-eq*: *do-full1-cp-step* $S \neq S \implies$

toS (*rough-state-of* S) \neq *toS* (*rough-state-of* (*do-full1-cp-step* S))

proof –

assume *a1*: *do-full1-cp-step* $S \neq S$

then have $S \neq \text{do-cp-step}' S$

by *fastforce*

then show *?thesis*

by (*metis* (*no-types*) *cp-step-is-cdcl_W-cp* *do-cp-step'-def* *do-cp-step-eq-no-step*
do-full1-cp-step-fix-point-of-do-full1-cp-step in-clauses-rough-state-of-is-distinct
rough-state-of-inverse)

qed

do-full1-cp-step should not be unfolded anymore:

declare *do-full1-cp-step.simps* [*simp del*]

Correction of the transformation **lemma** *do-cdcl_W-stgy-step*:

assumes *do-cdcl_W-stgy-step* $S \neq S$

shows *cdcl_W-stgy* (*toS* (*rough-state-of* S)) (*toS* (*rough-state-of* (*do-cdcl_W-stgy-step* S)))

proof (*cases* *do-full1-cp-step* $S = S$)

case *False*

then show *?thesis*

using *assms* *do-full1-cp-step-full* [of S] **unfolding** *full-unfold* *do-cdcl_W-stgy-step-def*

by (*auto* *intro!*: *cdcl_W-stgy.intros* *dest*: *toS-do-full1-cp-step-not-eq*)

next

case *True*

have *cdcl_W-o* (*toS* (*rough-state-of* S)) (*toS* (*rough-state-of* (*do-other-step'* S)))

by (*smt* *True* *assms* *cdcl_W-all-struct-inv-rough-state* *do-cdcl_W-stgy-step-def* *do-other-step*
rough-state-of-do-other-step' *rough-state-of-inverse*)

moreover

have

np: *no-step propagate* (*toS* (*rough-state-of* S)) **and**

nc: *no-step conflict* (*toS* (*rough-state-of* S))

```

    apply (metis True do-cp-step-eq-no-prop-no-conf
      do-full1-cp-step-fix-point-of-do-full1-cp-step do-propagate-step-no-step
      in-clauses-rough-state-of-is-distinct)
  by (metis True do-conflict-step-no-step do-cp-step-eq-no-prop-no-conf
    do-full1-cp-step-fix-point-of-do-full1-cp-step)
then have no-step cdclW-cp (toS (rough-state-of S))
  by (simp add: cdclW-cp.simps)
moreover have full cdclW-cp (toS (rough-state-of (do-other-step' S)))
  (toS (rough-state-of (do-full1-cp-step (do-other-step' S))))
  using do-full1-cp-step-full by auto
ultimately show ?thesis
  using assms True unfolding do-cdclW-stgy-step-def
  by (auto intro!: cdclW-stgy.other' dest: toS-do-full1-cp-step-not-eq)
qed

```

```

lemma length-trail-toS[simp]:
  length (trail (toS S)) = length (trail S)
  by (cases S) auto

```

```

lemma conflicting-noTrue-iff-toS[simp]:
  conflicting (toS S) ≠ C-True ⟷ conflicting S ≠ C-True
  by (cases S) auto

```

```

lemma trail-toS-neq-imp-trail-neq:
  trail (toS S) ≠ trail (toS S') ⟹ trail S ≠ trail S'
  by (cases S, cases S') auto

```

```

lemma do-skip-step-trail-changed-or-conflict:
  assumes d: do-other-step S ≠ S
  and inv: cdclW-all-struct-inv (toS S)
  shows trail S ≠ trail (do-other-step S)

```

proof –

```

  have M: ∧M K M1 c. M = c @ K # M1 ⟹ Suc (length M1) ≤ length M
    by auto
  have cdclW-M-level-inv (toS S)
    using inv unfolding cdclW-all-struct-inv-def by auto
  have cdclW-o (toS S) (toS (do-other-step S)) using do-other-step[OF inv d] .
  then show ?thesis
    using ⟨cdclW-M-level-inv (toS S)⟩
  proof (induction toS (do-other-step S) rule: cdclW-o-induct-lev2)
    case decide
    then show ?thesis
      by (auto simp add: trail-toS-neq-imp-trail-neq)[]
  next
  case (skip)
  then show ?case
    by (cases S; cases do-other-step S) force
  next
  case (resolve)
  then show ?case
    by (cases S, cases do-other-step S) force
  next
  case (backtrack K i M1 M2 L D) note decomp = this(1) and confl-S = this(3) and undef =
    this(6) and
    U = this(7)

```

```

have [simp]: cons-trail (Propagated L (D + {#L#}))
  (cdclW.reduce-trail-to M1
    (add-learned-cls (D + {#L#})
      (update-backtrack-lvl (get-maximum-level D (trail (toS S)))
        (update-conflicting C-True (toS S)))))
  =
  (Propagated L (D + {#L#})# M1, mset (map mset (clauses S)),
    {#D + {#L#}#} + mset (map mset (learned-clss S)),
    get-maximum-level D (trail (toS S)), C-True)
apply (subst state-conv[of cons-trail -])
using decomp undef by (cases S) auto
then show ?case
apply auto
apply (cases do-other-step S; auto split: split-if-asm simp: Let-def)
  apply (cases S rule: do-skip-step.cases; auto split: split-if-asm)
  apply (cases S rule: do-skip-step.cases; auto split: split-if-asm)

  apply (cases S rule: do-backtrack-step.cases;
    auto split: split-if-asm option.splits list.splits marked-lit.splits
    dest!: bt-cut-some-decomp)[]
using d apply (cases S rule: do-decide-step.cases; auto split: option.splits)[]
done
qed
qed

lemma do-full1-cp-step-induct:
  ( $\bigwedge S. (S \neq \text{do-cp-step}' S \implies P (\text{do-cp-step}' S)) \implies P S \implies P a0$ )
using do-full1-cp-step.induct by metis

lemma do-cp-step-neq-trail-increase:
   $\exists c. \text{trail} (\text{do-cp-step } S) = c @ \text{trail } S \wedge (\forall m \in \text{set } c. \neg \text{is-marked } m)$ 
by (cases S, cases conflicting S)
  (auto simp add: do-cp-step-def do-conflict-step-def do-propagate-step-def split: option.splits)

lemma do-full1-cp-step-neq-trail-increase:
   $\exists c. \text{trail} (\text{rough-state-of } (\text{do-full1-cp-step } S)) = c @ \text{trail} (\text{rough-state-of } S)$ 
   $\wedge (\forall m \in \text{set } c. \neg \text{is-marked } m)$ 
apply (induction rule: do-full1-cp-step-induct)
apply (case-tac do-cp-step' S = S)
apply (simp add: do-full1-cp-step.simps)
by (smt Un-iff append-assoc do-cp-step'-def do-cp-step-neq-trail-increase do-full1-cp-step.simps
  rough-state-of-state-of-do-cp-step set-append)

lemma do-cp-step-conflicting:
   $\text{conflicting} (\text{rough-state-of } S) \neq C\text{-True} \implies \text{do-cp-step}' S = S$ 
unfolding do-cp-step'-def do-cp-step-def by simp

lemma do-full1-cp-step-conflicting:
   $\text{conflicting} (\text{rough-state-of } S) \neq C\text{-True} \implies \text{do-full1-cp-step } S = S$ 
unfolding do-cp-step'-def do-cp-step-def
apply (induction rule: do-full1-cp-step-induct)
by (case-tac S  $\neq$  do-cp-step' S)
  (auto simp add: rough-state-of-inverse do-full1-cp-step.simps dest: do-cp-step-conflicting)

lemma do-decide-step-not-conflicting-one-more-decide:

```

assumes
conflicting $S = C\text{-True}$ **and**
do-decide-step $S \neq S$
shows $\text{Suc } (\text{length } (\text{filter is-marked } (\text{trail } S)))$
 $= \text{length } (\text{filter is-marked } (\text{trail } (\text{do-decide-step } S)))$
using *assms* **unfolding** *do-other-step'-def*
by (*cases* S) (*auto simp*: *Let-def split: split-if-asm option.splits*
dest!: *find-first-unused-var-Some-not-all-incl*)

lemma *do-decide-step-not-conflicting-one-more-decide-bt*:
assumes *conflicting* $S \neq C\text{-True}$ **and**
do-decide-step $S \neq S$
shows $\text{length } (\text{filter is-marked } (\text{trail } S)) < \text{length } (\text{filter is-marked } (\text{trail } (\text{do-decide-step } S)))$
using *assms* **unfolding** *do-other-step'-def* **by** (*cases* S , *cases conflicting* S)
(auto simp add: Let-def split: split-if-asm option.splits)

lemma *do-other-step-not-conflicting-one-more-decide-bt*:
assumes *conflicting* (*rough-state-of* S) $\neq C\text{-True}$ **and**
conflicting (*rough-state-of* (*do-other-step'* S)) $= C\text{-True}$ **and**
do-other-step' $S \neq S$
shows $\text{length } (\text{filter is-marked } (\text{trail } (\text{rough-state-of } S)))$
 $> \text{length } (\text{filter is-marked } (\text{trail } (\text{rough-state-of } (\text{do-other-step'} S))))$
proof (*cases* S , *goal-cases*)
case ($1\ y$) **note** $S = \text{this}(1)$ **and** $\text{inv} = \text{this}(2)$
obtain $M\ N\ U\ k\ E$ **where** $y: y = (M, N, U, k, C\text{-Clause } E)$
using *assms*(1) $S\ \text{inv}$ **by** (*cases* y , *cases conflicting* y) *auto*
have M : *rough-state-of* (*state-of* ($M, N, U, k, C\text{-Clause } E$)) $= (M, N, U, k, C\text{-Clause } E)$
using $\text{inv } y$ **by** (*auto simp add: state-of-inverse*)
have bt : *do-other-step'* $S = \text{state-of } (\text{do-backtrack-step } (\text{rough-state-of } S))$

using *assms*($1,2$) **apply** (*cases rough-state-of* (*do-other-step'* S))
apply (*auto simp add: Let-def do-other-step'-def*)
apply (*cases rough-state-of* S *rule: do-decide-step.cases*)
apply *auto*
done
show *?case*
using *assms*(2) S **unfolding** $bt\ y\ \text{inv}$
apply *simp*
by (*auto simp add: M*
split: option.splits
dest: bt-cut-some-decomp arg-cong[of - - $\lambda u. \text{length } (\text{filter is-marked } u)$])

qed

lemma *do-other-step-not-conflicting-one-more-decide*:
assumes *conflicting* (*rough-state-of* S) $= C\text{-True}$ **and**
do-other-step' $S \neq S$
shows $1 + \text{length } (\text{filter is-marked } (\text{trail } (\text{rough-state-of } S)))$
 $= \text{length } (\text{filter is-marked } (\text{trail } (\text{rough-state-of } (\text{do-other-step'} S))))$
proof (*cases* S , *goal-cases*)
case ($1\ y$) **note** $S = \text{this}(1)$ **and** $\text{inv} = \text{this}(2)$
obtain $M\ N\ U\ k$ **where** $y: y = (M, N, U, k, C\text{-True})$ **using** *assms*(1) $S\ \text{inv}$ **by** (*cases* y) *auto*
have M : *rough-state-of* (*state-of* ($M, N, U, k, C\text{-True}$)) $= (M, N, U, k, C\text{-True})$
using $\text{inv } y$ **by** (*auto simp add: state-of-inverse*)
have *state-of* (*do-decide-step* ($M, N, U, k, C\text{-True}$)) $\neq \text{state-of } (M, N, U, k, C\text{-True})$

```

    using assms(2) unfolding do-other-step'-def y inv S by (auto simp add: M)
  then have f4: do-skip-step (rough-state-of S) = rough-state-of S
    unfolding S M y by (metis (full-types) do-skip-step.simps(4))
  have f5: do-resolve-step (rough-state-of S) = rough-state-of S
    unfolding S M y by (metis (no-types) do-resolve-step.simps(4))
  have f6: do-backtrack-step (rough-state-of S) = rough-state-of S
    unfolding S M y by (metis (no-types) do-backtrack-step.simps(2))
  have do-other-step (rough-state-of S) ≠ rough-state-of S
    using assms(2) unfolding S M y do-other-step'-def by (metis (no-types))
  then show ?case
    using f6 f5 f4 by (simp add: assms(1) do-decide-step-not-conflicting-one-more-decide
      do-other-step'-def)
qed

```

lemma *rough-state-of-state-of-do-skip-step-rough-state-of[simp]:*
 $\text{rough-state-of } (\text{state-of } (\text{do-skip-step } (\text{rough-state-of } S))) = \text{do-skip-step } (\text{rough-state-of } S)$
by (smt do-other-step.simps rough-state-of-inverse rough-state-of-state-of-do-other-step)

lemma *conflicting-do-resolve-step-iff[iff]:*
 $\text{conflicting } (\text{do-resolve-step } S) = C\text{-True} \longleftrightarrow \text{conflicting } S = C\text{-True}$
by (cases S rule: do-resolve-step.cases)
(auto simp add: Let-def split: option.splits)

lemma *conflicting-do-skip-step-iff[iff]:*
 $\text{conflicting } (\text{do-skip-step } S) = C\text{-True} \longleftrightarrow \text{conflicting } S = C\text{-True}$
by (cases S rule: do-skip-step.cases)
(auto simp add: Let-def split: option.splits)

lemma *conflicting-do-decide-step-iff[iff]:*
 $\text{conflicting } (\text{do-decide-step } S) = C\text{-True} \longleftrightarrow \text{conflicting } S = C\text{-True}$
by (cases S rule: do-decide-step.cases)
(auto simp add: Let-def split: option.splits)

lemma *conflicting-do-backtrack-step-imp[simp]:*
 $\text{do-backtrack-step } S \neq S \implies \text{conflicting } (\text{do-backtrack-step } S) = C\text{-True}$
by (cases S rule: do-backtrack-step.cases)
(auto simp add: Let-def split: list.splits option.splits marked-lit.splits)

lemma *do-skip-step-eq-iff-trail-eq:*
 $\text{do-skip-step } S = S \longleftrightarrow \text{trail } (\text{do-skip-step } S) = \text{trail } S$
by (cases S rule: do-skip-step.cases) auto

lemma *do-decide-step-eq-iff-trail-eq:*
 $\text{do-decide-step } S = S \longleftrightarrow \text{trail } (\text{do-decide-step } S) = \text{trail } S$
by (cases S rule: do-decide-step.cases) (auto split: option.split)

lemma *do-backtrack-step-eq-iff-trail-eq:*
 $\text{do-backtrack-step } S = S \longleftrightarrow \text{trail } (\text{do-backtrack-step } S) = \text{trail } S$
by (cases S rule: do-backtrack-step.cases)
(auto split: option.split list.splits marked-lit.splits
dest!: bt-cut-in-get-all-marked-decomposition)

lemma *do-resolve-step-eq-iff-trail-eq:*
 $\text{do-resolve-step } S = S \longleftrightarrow \text{trail } (\text{do-resolve-step } S) = \text{trail } S$
by (cases S rule: do-resolve-step.cases) auto

lemma *do-other-step-eq-iff-trail-eq*:

trail (*do-other-step* *S*) = *trail* *S* \longleftrightarrow *do-other-step* *S* = *S*

by (*auto simp add*: *Let-def do-skip-step-eq-iff-trail-eq[symmetric]*)

do-decide-step-eq-iff-trail-eq[symmetric] *do-backtrack-step-eq-iff-trail-eq[symmetric]*

do-resolve-step-eq-iff-trail-eq[symmetric])

lemma *do-full1-cp-step-do-other-step'-normal-form[dest!]*:

assumes *H*: *do-full1-cp-step* (*do-other-step'* *S*) = *S*

shows *do-other-step'* *S* = *S* \wedge *do-full1-cp-step* *S* = *S*

proof –

let *?T* = *do-other-step'* *S*

{ **assume** *confl*: *conflicting* (*rough-state-of* *?T*) \neq *C-True*

then have *tr*: *trail* (*rough-state-of* (*do-full1-cp-step* *?T*)) = *trail* (*rough-state-of* *?T*)

using *do-full1-cp-step-conflicting* **by** *auto*

have *trail* (*rough-state-of* (*do-full1-cp-step* (*do-other-step'* *S*))) = *trail* (*rough-state-of* *S*)

using *arg-cong[OF H, of $\lambda S. \text{trail} (\text{rough-state-of } S)$]* .

then have *trail* (*rough-state-of* (*do-other-step'* *S*)) = *trail* (*rough-state-of* *S*)

by (*auto simp add*: *do-full1-cp-step-conflicting confl*)

then have *do-other-step'* *S* = *S*

by (*simp add*: *do-other-step-eq-iff-trail-eq do-other-step'-def rough-state-of-inverse*
del: *do-other-step.simps*)

}

moreover {

assume *eq[simp]*: *do-other-step'* *S* = *S*

obtain *c* **where** *c*: *trail* (*rough-state-of* (*do-full1-cp-step* *S*)) = *c* @ *trail* (*rough-state-of* *S*)

using *do-full1-cp-step-neq-trail-increase* **by** *auto*

moreover have *trail* (*rough-state-of* (*do-full1-cp-step* *S*)) = *trail* (*rough-state-of* *S*)

using *arg-cong[OF H, of $\lambda S. \text{trail} (\text{rough-state-of } S)$]* **by** *simp*

finally have *c* = [] **by** *blast*

then have *do-full1-cp-step* *S* = *S* **using** *assms* **by** *auto*

}

moreover {

assume *confl*: *conflicting* (*rough-state-of* *?T*) = *C-True* **and** *neg*: *do-other-step'* *S* \neq *S*

obtain *c* **where**

c: *trail* (*rough-state-of* (*do-full1-cp-step* *?T*)) = *c* @ *trail* (*rough-state-of* *?T*) **and**

nm: $\forall m \in \text{set } c. \neg \text{is-marked } m$

using *do-full1-cp-step-neq-trail-increase* **by** *auto*

have *length* (*filter is-marked* (*trail* (*rough-state-of* (*do-full1-cp-step* *?T*))))

= *length* (*filter is-marked* (*trail* (*rough-state-of* *?T*))) **using** *nm* **unfolding** *c* **by** *force*

moreover have *length* (*filter is-marked* (*trail* (*rough-state-of* *S*)))

\neq *length* (*filter is-marked* (*trail* (*rough-state-of* *?T*)))

using *do-other-step-not-conflicting-one-more-decide[OF - neg]*

do-other-step-not-conflicting-one-more-decide-bt[of S, OF - confl neg]

by *linarith*

finally have *False* **unfolding** *H* **by** *blast*

}

ultimately show *?thesis* **by** *blast*

qed

lemma *do-cdcl_W-stgy-step-no*:

assumes *S*: *do-cdcl_W-stgy-step* *S* = *S*

shows *no-step cdcl_W-stgy* (*toS* (*rough-state-of* *S*))

```

proof -
{
  fix S'
  assume full1 cdclW-cp (toS (rough-state-of S)) S'
  then have False
    using do-full1-cp-step-full[of S] unfolding full-def S rtrancpl-unfold full1-def
    by (smt assms do-cdclW-stgy-step-def trancplD)
}
moreover {
  fix S' S''
  assume cdclW-o (toS (rough-state-of S)) S' and
    no-step propagate (toS (rough-state-of S)) and
    no-step conflict (toS (rough-state-of S)) and
    full cdclW-cp S' S''
  then have False
    using assms unfolding do-cdclW-stgy-step-def
    by (smt cdclW-all-struct-inv-rough-state do-full1-cp-step-do-other-step'-normal-form
      do-other-step-no rough-state-of-do-other-step')
}
ultimately show ?thesis using assms by (force simp: cdclW-cp.simps cdclW-stgy.simps)
qed

lemma toS-rough-state-of-state-of-rough-state-from-init-state-of[simp]:
  toS (rough-state-of (state-of (rough-state-from-init-state-of S)))
  = toS (rough-state-from-init-state-of S)
  using rough-state-from-init-state-of[of S] by (auto simp add: state-of-inverse)

lemma cdclW-cp-is-rtrancpl-cdclW: cdclW-cp S T  $\implies$  cdclW** S T
  apply (induction rule: cdclW-cp.induct)
  using conflict apply blast
  using propagate by blast

lemma rtrancpl-cdclW-cp-is-rtrancpl-cdclW: cdclW-cp** S T  $\implies$  cdclW** S T
  apply (induction rule: rtrancpl-induct)
  apply simp
  by (fastforce dest!: cdclW-cp-is-rtrancpl-cdclW)

lemma cdclW-stgy-is-rtrancpl-cdclW:
  cdclW-stgy S T  $\implies$  cdclW** S T
  apply (induction rule: cdclW-stgy.induct)
  using cdclW-stgy.conflict' rtrancpl-cdclW-stgy-rtrancpl-cdclW apply blast
  unfolding full-def by (fastforce dest!: cdclW.other rtrancpl-cdclW-cp-is-rtrancpl-cdclW)

lemma cdclW-stgy-init-clss: cdclW-stgy S T  $\implies$  cdclW-M-level-inv S  $\implies$  clauses S = clauses T
  using rtrancpl-cdclW-init-clss cdclW-stgy-is-rtrancpl-cdclW by fast

lemma clauses-toS-rough-state-of-do-cdclW-stgy-step[simp]:
  clauses (toS (rough-state-of (do-cdclW-stgy-step (state-of (rough-state-from-init-state-of S)))))
  = clauses (toS (rough-state-from-init-state-of S)) (is - = clauses (toS ?S))
  apply (cases do-cdclW-stgy-step (state-of ?S) = state-of ?S)
  apply simp
  by (smt cdclW-all-struct-inv-def cdclW-all-struct-inv-rough-state cdclW-stgy-no-more-init-clss
    do-cdclW-stgy-step toS-rough-state-of-state-of-rough-state-from-init-state-of)

lemma rough-state-from-init-state-of-do-cdclW-stgy-step'[code abstract]:

```


$\text{rough-state-from-init-state-of } (\text{do-cdcl}_W\text{-stgy-step}' S) =$
 $\text{rough-state-of } (\text{do-cdcl}_W\text{-stgy-step } (\text{id-of-I-to } S))$
proof –
let $?S = (\text{rough-state-from-init-state-of } S)$
have $\text{cdcl}_W\text{-stgy}^{**} (S0\text{-cdcl}_W (\text{clauses } (\text{toS } (\text{rough-state-from-init-state-of } S))))$
 $(\text{toS } (\text{rough-state-from-init-state-of } S))$
using $\text{rough-state-from-init-state-of}[of\ S]$ **by** *auto*
moreover have $\text{cdcl}_W\text{-stgy}^{**}$
 $(\text{toS } (\text{rough-state-from-init-state-of } S))$
 $(\text{toS } (\text{rough-state-of } (\text{do-cdcl}_W\text{-stgy-step}$
 $(\text{state-of } (\text{rough-state-from-init-state-of } S))))))$
using $\text{do-cdcl}_W\text{-stgy-step}[of\ \text{state-of } ?S]$
by $(\text{cases } \text{do-cdcl}_W\text{-stgy-step } (\text{state-of } ?S) = \text{state-of } ?S)$ *auto*
ultimately show *?thesis*
unfolding $\text{do-cdcl}_W\text{-stgy-step}'\text{-def id-of-I-to-def}$ **by** $(\text{auto intro!}:\ \text{state-from-init-state-of-inverse})$
qed

All rules together function $\text{do-all-cdcl}_W\text{-stgy}$ **where**

$\text{do-all-cdcl}_W\text{-stgy } S =$
 $(\text{let } T = \text{do-cdcl}_W\text{-stgy-step}' S \text{ in}$
 $\text{if } T = S \text{ then } S \text{ else } \text{do-all-cdcl}_W\text{-stgy } T)$

by *fast+*

termination

proof $(\text{relation } \{(T, S)\})$.

$(\text{cdcl}_W\text{-measure } (\text{toS } (\text{rough-state-from-init-state-of } T))),$
 $\text{cdcl}_W\text{-measure } (\text{toS } (\text{rough-state-from-init-state-of } S)))$
 $\in \text{lexn } \{(a, b). a < b\} \exists\}$, *goal-cases*

case 1

show *?case* **by** $(\text{rule wf-if-measure-f}) (\text{auto intro!}:\ \text{wf-lexn wf-less})$

next

case $(2\ S\ T)$ **note** $T = \text{this}(1)$ **and** $ST = \text{this}(2)$

let $?S = \text{rough-state-from-init-state-of } S$

have $S: \text{cdcl}_W\text{-stgy}^{**} (S0\text{-cdcl}_W (\text{clauses } (\text{toS } ?S))) (\text{toS } ?S)$

using $\text{rough-state-from-init-state-of}[of\ S]$ **by** *auto*

moreover have $\text{cdcl}_W\text{-stgy } (\text{toS } (\text{rough-state-from-init-state-of } S))$

$(\text{toS } (\text{rough-state-from-init-state-of } T))$

using $ST\ \text{do-cdcl}_W\text{-stgy-step}$ **unfolding** T

by $(\text{smt id-of-I-to-def mem-Collect-eq rough-state-from-init-state-of}$
 $\text{rough-state-from-init-state-of-do-cdcl}_W\text{-stgy-step}' \text{ rough-state-from-init-state-of-inject}$
 $\text{state-of-inverse})$

moreover

have $\text{cdcl}_W\text{-all-struct-inv } (\text{toS } (\text{rough-state-from-init-state-of } S))$

using $\text{rough-state-from-init-state-of}[of\ S]$ **by** *auto*

then have $\text{cdcl}_W\text{-all-struct-inv } (S0\text{-cdcl}_W (\text{clauses } (\text{toS } (\text{rough-state-from-init-state-of } S))))$

by $(\text{cases } \text{rough-state-from-init-state-of } S)$

$(\text{auto simp add: } \text{cdcl}_W\text{-all-struct-inv-def distinct-cdcl}_W\text{-state-def})$

ultimately show *?case*

by $(\text{auto intro!}:\ \text{cdcl}_W\text{-stgy-step-decreasing}[of\ -\ -\ S0\text{-cdcl}_W (\text{clauses } (\text{toS } ?S))]$
 $\text{simp del: } \text{cdcl}_W\text{-measure.simps})$

qed

thm $\text{do-all-cdcl}_W\text{-stgy.induct}$

lemma $\text{do-all-cdcl}_W\text{-stgy.induct}:$

$(\bigwedge S. (\text{do-cdcl}_W\text{-stgy-step}' S \neq S \implies P (\text{do-cdcl}_W\text{-stgy-step}' S)) \implies P S) \implies P a0$

using $\text{do-all-cdcl}_W\text{-stgy.induct}$ **by** *metis*

```

lemma no-step-cdclW-stgy-cdclW-all:
  no-step cdclW-stgy (toS (rough-state-from-init-state-of (do-all-cdclW-stgy S)))
  apply (induction S rule:do-all-cdclW-stgy-induct)
  apply (case-tac do-cdclW-stgy-step' S ≠ S)
proof –
  fix Sa :: cdclW-state-inv-from-init-state
  assume a1: ¬ do-cdclW-stgy-step' Sa ≠ Sa
  { fix pp
    have (if True then Sa else do-all-cdclW-stgy Sa) = do-all-cdclW-stgy Sa
      using a1 by auto
    then have ¬ cdclW-stgy (toS (rough-state-from-init-state-of (do-all-cdclW-stgy Sa))) pp
      using a1 by (metis (no-types) do-cdclW-stgy-step-no id-of-I-to-def
        rough-state-from-init-state-of-do-cdclW-stgy-step' rough-state-of-inverse) }
    then show no-step cdclW-stgy (toS (rough-state-from-init-state-of (do-all-cdclW-stgy Sa)))
      by fastforce
  }
next
  fix Sa :: cdclW-state-inv-from-init-state
  assume a1: do-cdclW-stgy-step' Sa ≠ Sa
    ⇒ no-step cdclW-stgy (toS (rough-state-from-init-state-of (do-all-cdclW-stgy (do-cdclW-stgy-step' Sa))))
  assume a2: do-cdclW-stgy-step' Sa ≠ Sa
  have do-all-cdclW-stgy Sa = do-all-cdclW-stgy (do-cdclW-stgy-step' Sa)
    by (metis (full-types) do-all-cdclW-stgy.simps)
  then show no-step cdclW-stgy (toS (rough-state-from-init-state-of (do-all-cdclW-stgy Sa)))
    using a2 a1 by presburger
qed

lemma do-all-cdclW-stgy-is-rtrancpl-cdclW-stgy:
  cdclW-stgy** (toS (rough-state-from-init-state-of S))
  (toS (rough-state-from-init-state-of (do-all-cdclW-stgy S)))
  apply (induction S rule: do-all-cdclW-stgy-induct)
  apply (case-tac do-cdclW-stgy-step' S = S)
  apply simp
  by (smt converse-rtrancpl-into-rtrancpl do-all-cdclW-stgy.simps do-cdclW-stgy-step id-of-I-to-def
    rough-state-from-init-state-of-do-cdclW-stgy-step'
    toS-rough-state-of-state-of-rough-state-from-init-state-of)

```

Final theorem:

lemma *DPLL-tot-correct:*

```

assumes
  r: rough-state-from-init-state-of (do-all-cdclW-stgy (state-from-init-state-of
    ([], map remdups N, [], 0, C-True))) = S and
  S: (M', N', U', k, E) = toS S
shows (E ≠ C-Clause {#} ∧ satisfiable (set (map mset N)))
  ∨ (E = C-Clause {#} ∧ unsatisfiable (set (map mset N)))
proof –
  let ?N = map remdups N
  have inv: cdclW-all-struct-inv (toS ([], map remdups N, [], 0, C-True))
    unfolding cdclW-all-struct-inv-def distinct-cdclW-state-def distinct-mset-set-def by auto
  then have S0: rough-state-of (state-of ([], map remdups N, [], 0, C-True))
    = ([], map remdups N, [], 0, C-True) by simp
  have 1: full cdclW-stgy (toS ([], ?N, [], 0, C-True)) (toS S)
    unfolding full-def apply rule
    using do-all-cdclW-stgy-is-rtrancpl-cdclW-stgy [of

```

```

state-from-init-state-of ([], map remdups N, [], 0, C-True)] inv
no-step-cdclW-stgy-cdclW-all
by (auto simp del: do-all-cdclW-stgy.simps simp: state-from-init-state-of-inverse
r[symmetric])+
moreover have 2: finite (set (map mset ?N)) by auto
moreover have 3: distinct-mset-set (set (map mset ?N))
  unfolding distinct-mset-set-def by auto
moreover
  have cdclW-all-struct-inv (toS S)
    by (metis (no-types) cdclW-all-struct-inv-rough-state r
toS-rough-state-of-state-of-rough-state-from-init-state-of)
  then have cons: consistent-interp (lits-of M')
    unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def S[symmetric] by auto
moreover
  have clauses (toS ([], ?N, [], 0, C-True)) = clauses (toS S)
    apply (rule rtrancp-cdclW-init-clss)
    using 1 unfolding full-def by (auto simp add: rtrancp-cdclW-stgy-rtrancp-cdclW)
  then have N': mset (map mset ?N) = N'
    using S[symmetric] by auto
have (E ≠ C-Clause {#} ∧ satisfiable (set (map mset ?N)))
  ∨ (E = C-Clause {#} ∧ unsatisfiable (set (map mset ?N)))
  using full-cdclW-stgy-final-state-conclusive unfolding N' apply rule
    using 1 apply simp
    using 2 apply simp
    using 3 apply simp
    using S[symmetric] N' apply auto[1]
  using S[symmetric] N' cons by (fastforce simp: true-annots-true-cl)
then show ?thesis by auto
qed

```

The Code The SML code is skipped in the documentation, but stays to ensure that some version of the exported code is working

```

end
theory CDCL-WNOT
imports CDCL-W-Termination CDCL-NOT
begin

```

19 Link between Weidenbach's and NOT's CDCL

19.1 Inclusion of the states

```

declare upt.simps(2)[simp del]
sledgehammer-params[verbose]

```

```

context cdclW-ops
begin

```

```

lemma backtrack-levE:
  backtrack S S' ⇒ cdclW-M-level-inv S ⇒
  (∧ D L K M1 M2.
    (Marked K (Suc (get-maximum-level D (trail S))) # M1, M2)
    ∈ set (get-all-marked-decomposition (trail S)) ⇒
    get-level L (trail S) = get-maximum-level (D + {#L#}) (trail S) ⇒
    undefined-lit M1 L ⇒
  )

```

$S' \sim \text{cons-trail } (\text{Propagated } L \ (D + \{\#L\# \}))$
 $(\text{reduce-trail-to } M1 \ (\text{add-learned-cls } (D + \{\#L\# \}))$
 $(\text{update-backtrack-lvl } (\text{get-maximum-level } D \ (\text{trail } S)) \ (\text{update-conflicting } C\text{-True } S))) \implies$
 $\text{backtrack-lvl } S = \text{get-maximum-level } (D + \{\#L\# \}) \ (\text{trail } S) \implies$
 $\text{conflicting } S = C\text{-Clause } (D + \{\#L\# \}) \implies P \implies$
 P
using *assms* **by** (*induction rule: backtrack-induction-lev2*) *metis*

lemma *backtrack-no-cdcl_W-bj*:
assumes *cdcl*: *cdcl_W-bj* *T U* **and** *inv*: *cdcl_W-M-level-inv* *V*
shows $\neg \text{backtrack } V \ T$
using *cdcl inv*
by (*induction rule: cdcl_W-bj.induct*) (*force elim!: backtrack-levE[OF - inv]*)
simp: cdcl_W-M-level-inv-def+)

abbreviation *skip-or-resolve* :: $'st \Rightarrow 'st \Rightarrow \text{bool}$ **where**
skip-or-resolve $\equiv (\lambda S \ T. \text{skip } S \ T \vee \text{resolve } S \ T)$

lemma *rtrancpl-cdcl_W-bj-skip-or-resolve-backtrack*:
assumes *cdcl_W-bj*** *S U* **and** *inv*: *cdcl_W-M-level-inv* *S*
shows *skip-or-resolve*** *S U* $\vee (\exists T. \text{skip-or-resolve** } S \ T \wedge \text{backtrack } T \ U)$
using *assms*
proof (*induction*)
case *base*
then show ?*case* **by** *simp*
next
case (*step* *U V*) **note** *st* = *this(1)* **and** *bj* = *this(2)* **and** *IH* = *this(3)[OF this(4)]*
consider
 $(SU) \ S = U$
 $| (SUP) \ \text{cdcl}_W\text{-bj}^{++} \ S \ U$
using *st unfolding rtrancpl-unfold by blast*
then show ?*case*
proof *cases*
case *SUp*
have $\bigwedge T. \text{skip-or-resolve** } S \ T \implies \text{cdcl}_W^{**} \ S \ T$
using *mono-rtrancpl[of skip-or-resolve cdcl_W] other by blast*
then have *skip-or-resolve*** *S U*
using *bj IH inv backtrack-no-cdcl_W-bj rtrancpl-cdcl_W-consistent-inv[OF - inv] by meson*
then show ?*thesis*
using *bj by (metis (no-types, lifting) cdcl_W-bj.cases rtrancpl.simps)*
next
case *SU*
then show ?*thesis*
using *bj by (metis (no-types, lifting) cdcl_W-bj.cases rtrancpl.simps)*
qed
qed

lemma *rtrancpl-skip-or-resolve-rtrancpl-cdcl_W*:
*skip-or-resolve*** *S T* $\implies \text{cdcl}_W^{**} \ S \ T$
by (*induction rule: rtrancpl-induct*) (*auto dest!: cdcl_W-bj.intros cdcl_W.intros cdcl_W-o.intros*)

abbreviation *backjump-l-cond* :: $'v \text{ literal multiset} \Rightarrow 'v \text{ literal} \Rightarrow 'st \Rightarrow \text{bool}$ **where**
backjump-l-cond $\equiv \lambda C \ L \ S. \text{True}$

definition $inv_{NOT} :: 'st \Rightarrow bool$ **where**
 $inv_{NOT} \equiv \lambda S. no_dup \ (trail \ S)$

declare $inv_{NOT}\text{-def}[simp]$
end

fun $convert\text{-}trail\text{-}from\text{-}W ::$
 $('v, 'lv, 'v \text{ literal multiset}) \text{ marked-lit list}$
 $\Rightarrow ('v, unit, unit) \text{ marked-lit list}$ **where**
 $convert\text{-}trail\text{-}from\text{-}W \ [] = [] \mid$
 $convert\text{-}trail\text{-}from\text{-}W \ (Propagated \ L \ - \ \# \ M) = Propagated \ L \ () \ \# \ convert\text{-}trail\text{-}from\text{-}W \ M \mid$
 $convert\text{-}trail\text{-}from\text{-}W \ (Marked \ L \ - \ \# \ M) = Marked \ L \ () \ \# \ convert\text{-}trail\text{-}from\text{-}W \ M$

lemma $atm\text{-}convert\text{-}trail\text{-}from\text{-}W[simp]$:
 $(\lambda l. atm\text{-}of \ (lit\text{-}of \ l)) \text{ ' set } (convert\text{-}trail\text{-}from\text{-}W \ xs) = (\lambda l. atm\text{-}of \ (lit\text{-}of \ l)) \text{ ' set } xs$
by (induction rule: marked-lit-list-induct) simp-all

lemma $no_dup\text{-}convert\text{-}from\text{-}W[simp]$:
 $no_dup \ (convert\text{-}trail\text{-}from\text{-}W \ M) \longleftrightarrow no_dup \ M$
by (induction rule: marked-lit-list-induct) simp-all

lemma $lits\text{-}of\text{-}convert\text{-}trail\text{-}from\text{-}W[simp]$:
 $lits\text{-}of \ (convert\text{-}trail\text{-}from\text{-}W \ M) = lits\text{-}of \ M$
by (induction rule: marked-lit-list-induct) simp-all

lemma $convert\text{-}trail\text{-}from\text{-}W\text{-}true\text{-}annots[simp]$:
 $convert\text{-}trail\text{-}from\text{-}W \ M \models_{as} C \longleftrightarrow M \models_{as} C$
by (auto simp: true-annots-true-cls)

lemma $defined\text{-}lit\text{-}convert\text{-}trail\text{-}from\text{-}W[simp]$:
 $defined\text{-}lit \ (convert\text{-}trail\text{-}from\text{-}W \ S) \ L \longleftrightarrow defined\text{-}lit \ S \ L$
by (auto simp: defined-lit-map)

lemma $convert\text{-}trail\text{-}from\text{-}W\text{-}append[simp]$:
 $convert\text{-}trail\text{-}from\text{-}W \ (M \ @ \ M') = convert\text{-}trail\text{-}from\text{-}W \ M \ @ \ convert\text{-}trail\text{-}from\text{-}W \ M'$
by (induction M rule: marked-lit-list-induct) simp-all

lemma $length\text{-}convert\text{-}trail\text{-}from\text{-}W[simp]$:
 $length \ (convert\text{-}trail\text{-}from\text{-}W \ W) = length \ W$
by (induction W rule: convert-trail-from-W.induct) auto

lemma $convert\text{-}trail\text{-}from\text{-}W\text{-}nil\text{-}iff[simp]$: $convert\text{-}trail\text{-}from\text{-}W \ S = [] \longleftrightarrow S = []$
by (induction S rule: convert-trail-from-W.induct) auto

The values 0 and $\{\#\}$ do not matter.

fun $convert\text{-}marked\text{-}lit\text{-}from\text{-}NOT$ **where**
 $convert\text{-}marked\text{-}lit\text{-}from\text{-}NOT \ (Propagated \ L \ -) = Propagated \ L \ \{\#\} \mid$
 $convert\text{-}marked\text{-}lit\text{-}from\text{-}NOT \ (Marked \ L \ -) = Marked \ L \ 0$

fun $convert\text{-}trail\text{-}from\text{-}NOT ::$
 $('v, unit, unit) \text{ marked-lit list}$
 $\Rightarrow ('v, nat, 'v \text{ literal multiset}) \text{ marked-lit list}$ **where**
 $convert\text{-}trail\text{-}from\text{-}NOT \ [] = [] \mid$
 $convert\text{-}trail\text{-}from\text{-}NOT \ (L \ \# \ M) = convert\text{-}marked\text{-}lit\text{-}from\text{-}NOT \ L \ \# \ convert\text{-}trail\text{-}from\text{-}NOT \ M$

lemma *convert-trail-from-W-from-NOT[simp]:*
 $\text{convert-trail-from-W } (\text{convert-trail-from-NOT } M) = M$
by (*induction rule: marked-lit-list-induct*) *auto*

lemma *convert-trail-from-W-cons-convert-lit-from-NOT[simp]:*
 $\text{convert-trail-from-W } (\text{convert-marked-lit-from-NOT } L \# M) = L \# \text{convert-trail-from-W } M$
by (*cases L*) *auto*

lemma *convert-trail-from-W-tl[simp]:*
 $\text{convert-trail-from-W } (\text{tl } M) = \text{tl } (\text{convert-trail-from-W } M)$
by (*induction rule: convert-trail-from-W.induct*) *simp-all*

lemma *length-convert-trail-from-NOT[simp]:*
 $\text{length } (\text{convert-trail-from-NOT } W) = \text{length } W$
by (*induction W rule: convert-trail-from-NOT.induct*) *auto*

abbreviation $\text{trail}_{\text{NOT}}$ **where**
 $\text{trail}_{\text{NOT}} \equiv \text{convert-trail-from-W } o \text{ fst}$

lemma *undefined-lit-convert-trail-from-W[iff]:*
 $\text{undefined-lit } (\text{convert-trail-from-W } M) L \longleftrightarrow \text{undefined-lit } M L$
by (*auto simp: defined-lit-map*)

lemma *lit-of-convert-marked-lit-from-NOT[iff]:*
 $\text{lit-of } (\text{convert-marked-lit-from-NOT } L) = \text{lit-of } L$
by (*cases L*) *auto*

sublocale $\text{state}_W \subseteq \text{dpll-state } \text{convert-trail-from-W } o \text{ trail clauses}$
 $\lambda L S. \text{cons-trail } (\text{convert-marked-lit-from-NOT } L) S$
 $\lambda S. \text{tl-trail } S$
 $\lambda C S. \text{add-learned-cls } C S$
 $\lambda C S. \text{remove-cls } C S$
by *unfold-locales auto*

sublocale $\text{cdcl}_W\text{-ops} \subseteq \text{cdcl}_{\text{NOT}}\text{-merge-bj-learn-ops } \text{convert-trail-from-W } o \text{ trail clauses}$
 $\lambda L S. \text{cons-trail } (\text{convert-marked-lit-from-NOT } L) S$
 $\lambda S. \text{tl-trail } S$
 $\lambda C S. \text{add-learned-cls } C S$
 $\lambda C S. \text{remove-cls } C S$
 $\lambda - . \text{True}$
 $\lambda - S. \text{conflicting } S = C\text{-True } \lambda C L S. \text{backjump-l-cond } C L S$
 $\wedge \text{distinct-mset } (C + \{\#L\}) \wedge \neg \text{tautology } (C + \{\#L\})$
by *unfold-locales*

sublocale $\text{cdcl}_W\text{-ops} \subseteq \text{cdcl}_{\text{NOT}}\text{-merge-bj-learn-proxy } \text{convert-trail-from-W } o \text{ trail clauses}$
 $\lambda L S. \text{cons-trail } (\text{convert-marked-lit-from-NOT } L) S$
 $\lambda S. \text{tl-trail } S$
 $\lambda C S. \text{add-learned-cls } C S$
 $\lambda C S. \text{remove-cls } C S$
 $\lambda - . \text{True}$
 $\lambda - S. \text{conflicting } S = C\text{-True } \text{backjump-l-cond } \text{inv}_{\text{NOT}}$
proof (*unfold-locales, goal-cases*)
case 2
then show ?*case* **using** $\text{cdcl}_{\text{NOT}}\text{-merged-bj-learn-no-dup-inv}$ **by** *auto*
next
case (1 $C' S C F' K F L$)

```

moreover
  let  $?C' = \text{remdups-mset } C'$ 
  have  $L \notin \# C'$ 
    using  $\langle F \models_{as} CNot \ C' \rangle \langle \text{undefined-lit } F \ L \rangle \text{Marked-Propagated-in-iff-in-lits-of}$ 
     $\text{in-}CNot\text{-implies-uminus}(2)$  by blast
  then have  $\text{distinct-mset } (?C' + \{\#L\# \})$ 
    by  $(\text{metis count-mset-set}(3) \text{distinct-mset-remdups-mset distinct-mset-single-add}$ 
     $\text{less-irrefl-nat mem-set-mset-iff remdups-mset-def})$ 
moreover
  have no-dup  $F$ 
    using  $\langle \text{inv}_{NOT} \ S \rangle \langle (\text{convert-trail-from-}W \circ \text{trail}) \ S = F' @ \text{Marked } K \ () \ \# \ F \rangle$ 
    unfolding  $\text{inv}_{NOT}\text{-def}$ 
    by  $(\text{smt comp-apply distinct.simps}(2) \text{distinct-append list.simps}(9) \text{map-append}$ 
     $\text{no-dup-convert-from-}W)$ 
  then have consistent-interp  $(\text{lits-of } F)$ 
    using distinctconsistent-interp by blast
  then have  $\neg \text{tautology } (C')$ 
    using  $\langle F \models_{as} CNot \ C' \rangle \text{consistent-}CNot\text{-not-tautology true-annots-true-cls}$  by blast
  then have  $\neg \text{tautology } (?C' + \{\#L\# \})$ 
    using  $\langle F \models_{as} CNot \ C' \rangle \langle \text{undefined-lit } F \ L \rangle$  by  $(\text{metis } CNot\text{-remdups-mset}$ 
     $\text{Marked-Propagated-in-iff-in-lits-of add.commute in-}CNot\text{-uminus tautology-add-single}$ 
     $\text{tautology-remdups-mset true-annot-singleton true-annots-def})$ 
show  $?case$ 
proof –
  have  $f2: \text{no-dup } ((\text{convert-trail-from-}W \circ \text{trail}) \ S)$ 
    using  $\langle \text{inv}_{NOT} \ S \rangle$  unfolding  $\text{inv}_{NOT}\text{-def}$  by simp
  have  $f3: \text{atm-of } L \in \text{atms-of-msu } (\text{clauses } S)$ 
     $\cup \text{atm-of 'lits-of } ((\text{convert-trail-from-}W \circ \text{trail}) \ S)$ 
    using  $\langle (\text{convert-trail-from-}W \circ \text{trail}) \ S = F' @ \text{Marked } K \ () \ \# \ F \rangle$ 
     $\langle \text{atm-of } L \in \text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of 'lits-of } (F' @ \text{Marked } K \ () \ \# \ F) \rangle$  by presburger
  have  $f4: \text{clauses } S \models_{pm} \text{remdups-mset } C' + \{\#L\# \}$ 
    by  $(\text{metis } (\text{no-types}) \langle L \notin \# C' \rangle \langle \text{clauses } S \models_{pm} C' + \{\#L\# \} \rangle \text{remdups-mset-singleton-sum}(2)$ 
     $\text{true-clss-cls-remdups-mset union-commute})$ 
  have  $F \models_{as} CNot \ (\text{remdups-mset } C')$ 
    by  $(\text{simp add: } \langle F \models_{as} CNot \ C' \rangle)$ 
  then show  $?thesis$ 
    using  $f4 \ f3 \ f2 \ \neg \text{tautology } (\text{remdups-mset } C' + \{\#L\# \})$  backjump-l.intros calculation(2-5,9)
     $\text{state-eq}_{NOT}\text{-ref}$  by blast
qed
qed

```

```

sublocale  $\text{cdcl}_W\text{-ops} \subseteq \text{cdcl}_{NOT}\text{-merge-bj-learn-proxy2}$  convert-trail-from-}W \circ \text{trail clauses}
   $\lambda L \ S. \text{cons-trail } (\text{convert-marked-lit-from-NOT } L) \ S$ 
   $\lambda S. \text{tl-trail } S$ 
   $\lambda C \ S. \text{add-learned-cls } C \ S$ 
   $\lambda C \ S. \text{remove-cls } C \ S \ \lambda - \cdot. \text{True } \text{inv}_{NOT}$ 
   $\lambda - \ S. \text{conflicting } S = C\text{-True backjump-l-cond}$ 
by unfold-locales

```

```

sublocale  $\text{cdcl}_W\text{-ops} \subseteq \text{cdcl}_{NOT}\text{-merge-bj-learn}$  convert-trail-from-}W \circ \text{trail clauses}
   $\lambda L \ S. \text{cons-trail } (\text{convert-marked-lit-from-NOT } L) \ S$ 
   $\lambda S. \text{tl-trail } S$ 
   $\lambda C \ S. \text{add-learned-cls } C \ S$ 
   $\lambda C \ S. \text{remove-cls } C \ S \ \lambda - \cdot. \text{True } \text{inv}_{NOT}$ 
   $\lambda - \ S. \text{conflicting } S = C\text{-True backjump-l-cond}$ 

```

```

apply unfold-locales
using dpll-bj-no-dup apply simp
using cdclNOT.simps cdclNOT-no-dup by auto

```

```

context cdclW-ops
begin

```

Notations are lost while proving locale inclusion:

```

notation state-eqNOT (infix  $\sim_{NOT}$  50)

```

19.2 More lemmas conflict-propagate and backjumping

19.2.1 Termination

lemma *cdcl_W-cp-normalized-element-all-inv*:

```

assumes inv: cdclW-all-struct-inv S
obtains T where full cdclW-cp S T
using assms cdclW-cp-normalized-element unfolding cdclW-all-struct-inv-def by blast
thm backtrackE

```

lemma *cdcl_W-bj-measure*:

```

assumes cdclW-bj S T and cdclW-M-level-inv S
shows length (trail S) + (if conflicting S = C-True then 0 else 1)
  > length (trail T) + (if conflicting T = C-True then 0 else 1)
using assms by (induction rule: cdclW-bj.induct)
(fastforce dest:arg-cong[of - - length])
intro: get-all-marked-decomposition-exists-prepend
elim!: backtrack-levE
simp: cdclW-M-level-inv-def+)

```

lemma *wf-cdcl_W-bj*:

```

wf {(b,a). cdclW-bj a b  $\wedge$  cdclW-M-level-inv a}
apply (rule wfP-if-measure[of  $\lambda$ -. True
  -  $\lambda T$ . length (trail T) + (if conflicting T = C-True then 0 else 1), simplified])
using cdclW-bj-measure by blast

```

lemma *cdcl_W-bj-exists-normal-form*:

```

assumes lev: cdclW-M-level-inv S
shows  $\exists T$ . full cdclW-bj S T

```

proof –

```

obtain T where T: full ( $\lambda a$  b. cdclW-bj a b  $\wedge$  cdclW-M-level-inv a) S T
using wf-exists-normal-form-full[OF wf-cdclW-bj] by auto
then have cdclW-bj** S T
by (auto dest: rtrancp-and-rtrancp-left simp: full-def)
moreover
then have cdclW** S T
using mono-rtrancp[of cdclW-bj cdclW] cdclW.simps by blast
then have cdclW-M-level-inv T
using rtrancp-cdclW-consistent-inv lev by auto
ultimately show ?thesis using T unfolding full-def by auto

```

qed

lemma *rtrancp-skip-state-decomp*:

```

assumes skip** S T and no-dup (trail S)
shows
 $\exists M$ . trail S = M @ trail T  $\wedge$  ( $\forall m \in \text{set } M$ .  $\neg \text{is-marked } m$ ) and

```


$T \sim \text{delete-trail-and-rebuild } (\text{trail } T) S$
using *assms* **by** (*induction rule: rtrancpl-induct*) (*auto simp del: state-simp simp: state-eq-def*)+

19.2.2 More backjumping

Backjumping after skipping or jump directly lemma *rtrancpl-skip-backtrack-backtrack*:

```

assumes
  skip**  $S T$  and
  backtrack  $T W$  and
   $\text{cdcl}_W\text{-all-struct-inv } S$ 
shows  $\text{backtrack } S W$ 
using assms
proof induction
  case base
  then show ?case by simp
next
  case (step  $T V$ ) note  $st = \text{this}(1)$  and  $skip = \text{this}(2)$  and  $IH = \text{this}(3)$  and  $bt = \text{this}(4)$  and
     $inv = \text{this}(5)$ 
  have  $skip^{**} S V$ 
    using  $st skip$  by auto
  then have  $\text{cdcl}_W\text{-all-struct-inv } V$ 
    using  $\text{rtrancpl-mono}[\text{of } skip \text{ cdcl}_W] \text{ assms}(3) \text{ rtrancpl-cdcl}_W\text{-all-struct-inv-inv mono-rtrancpl}$ 
    by (auto dest!: bj other cdclW-bj.skip)
  then have  $\text{cdcl}_W\text{-M-level-inv } V$ 
    unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$  by auto
  then obtain  $N k M1 M2 K D L U i$  where
     $V: \text{state } V = (\text{trail } V, N, U, k, C\text{-Clause } (D + \{\#L\# \}))$  and
     $W: \text{state } W = (\text{Propagated } L (D + \{\#L\# \}) \# M1, N, \{\#D + \{\#L\# \}\# \} + U,$ 
     $\text{get-maximum-level } D (\text{trail } V), C\text{-True})$  and
     $\text{decomp}: (\text{Marked } K (\text{Suc } i) \# M1, M2)$ 
     $\in \text{set } (\text{get-all-marked-decomposition } (\text{trail } V))$  and
     $k = \text{get-maximum-level } (D + \{\#L\# \}) (\text{trail } V)$  and
     $\text{lev-}L: \text{get-level } L (\text{trail } V) = k$  and
     $\text{undef}: \text{undefined-lit } M1 L$  and
     $W \sim \text{cons-trail } (\text{Propagated } L (D + \{\#L\# \}))$ 
     $(\text{reduce-trail-to } M1 (\text{add-learned-cls } (D + \{\#L\# \}))$ 
     $(\text{update-backtrack-lvl } (\text{get-maximum-level } D (\text{trail } V)) (\text{update-conflicting } C\text{-True } V))))$  and
     $\text{lev-l-}D: \text{backtrack-lvl } V = \text{get-maximum-level } (D + \{\#L\# \}) (\text{trail } V)$  and
     $\text{conflicting } V = C\text{-Clause } (D + \{\#L\# \})$  and
     $i: i = \text{get-maximum-level } D (\text{trail } V)$ 
    using  $bt$  by (elim backtrack-levE) (auto simp: cdclW-M-level-inv-decomp)
  let ? $D = (D + \{\#L\# \})$ 
  obtain  $L' C'$  where
     $T: \text{state } T = (\text{Propagated } L' C' \# \text{trail } V, N, U, k, C\text{-Clause } ?D)$  and
     $V \sim \text{tl-trail } T$  and
     $-L' \notin \# ?D$  and
     $?D \neq \{\# \}$ 
    using  $skip V$  by force

  let ? $M = \text{Propagated } L' C' \# \text{trail } V$ 
  have  $\text{cdcl}_W^{**} S T$  using  $\text{bj cdcl}_W\text{-bj.skip mono-rtrancpl}[\text{of } skip \text{ cdcl}_W S T]$  other st by meson
  then have  $\text{inv}': \text{cdcl}_W\text{-all-struct-inv } T$ 
    using  $\text{rtrancpl-cdcl}_W\text{-all-struct-inv-inv inv}$  by blast
  have  $\text{M-lev}: \text{cdcl}_W\text{-M-level-inv } T$  using  $\text{inv}'$  unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$  by auto
  then have  $\text{n-d}': \text{no-dup } ?M$ 
    using  $T$  unfolding  $\text{cdcl}_W\text{-M-level-inv-def}$  by auto

```

```

have  $k > 0$ 
  using decomp M-lev T V unfolding cdclW-M-level-inv-def by auto
then have atm-of L ∈ atm-of ‘ lits-of (trail V)
  using lev-L get-rev-level-ge-0-atm-of-in V by fastforce
then have L-L': atm-of L ≠ atm-of L'
  using n-d' unfolding lits-of-def by auto
have L'-M: atm-of L' ∉ atm-of ‘ lits-of (trail V)
  using n-d' unfolding lits-of-def by auto
have ?M ⊨as CNot ?D
  using inv' T unfolding cdclW-conflicting-def cdclW-all-struct-inv-def by auto
then have L' ∉# ?D
  using L-L' L'-M unfolding true-annots-def by (auto simp add: true-annot-def true-cls-def
    atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set Ball-mset-def
    split: split-if-asm)
have [simp]: trail (reduce-trail-to M1 T) = M1
  by (metis (mono-tags, lifting) One-nat-def Pair-inject T ⟨V ∼ tl-trail T⟩ decomp
    diff-less in-get-all-marked-decomposition-trail-update-trail length-greater-0-conv
    length-tl lessI list.distinct(1) reduce-trail-to-length-ne state-eq-trail
    trail-reduce-trail-to-length-le trail-tl-trail)
have skip** S V
  using st skip by auto
have no-dup (trail S)
  using inv unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def by auto
then have [simp]: init-cls S = N and [simp]: learned-cls S = U
  using rtrancp-skip-state-decomp[OF ⟨skip** S V⟩] V
  by (auto simp del: state-simp simp: state-eq-def)
then have W-S: W ∼ cons-trail (Propagated L (D + {#L#})) (reduce-trail-to M1
  (add-learned-cls (D + {#L#}) (update-backtrack-lvl i (update-conflicting C-True T))))
  using W i T undef M-lev by (auto simp del: state-simp simp: state-eq-def cdclW-M-level-inv-def)

obtain M2' where
  (Marked K (i+1) # M1, M2' ∈ set (get-all-marked-decomposition ?M)
  using decomp V by (cases hd (get-all-marked-decomposition (trail V)),
    cases get-all-marked-decomposition (trail V)) auto
moreover
  from L-L' have get-level L ?M = k
    using lev-L ⟨-L' ∉# ?D⟩ V by (auto split: split-if-asm)
moreover
  have atm-of L' ∉ atms-of D
    using ⟨L' ∉# ?D⟩ ⟨-L' ∉# ?D⟩ by (simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
      atms-of-def)
  then have get-level L ?M = get-maximum-level (D+{#L#}) ?M
    using lev-l-D[symmetric] L-L' V lev-L by simp
moreover have i = get-maximum-level D ?M
  using i ⟨atm-of L' ∉ atms-of D⟩ by auto
moreover

ultimately have backtrack T W
  using T(1) W-S by blast
then show ?thesis using IH inv by blast
qed

```

lemma *fst-get-all-marked-decomposition-prepend-not-marked:*
assumes $\forall m \in \text{set } MS. \neg \text{is-marked } m$

shows *set (map fst (get-all-marked-decomposition M))*
 = *set (map fst (get-all-marked-decomposition (MS @ M)))*
using *assms apply (induction MS rule: marked-lit-list-induct)*
apply *auto[2]*
by *(case-tac get-all-marked-decomposition (xs @ M)) simp-all*

See also $\llbracket \text{skip}^{**} ?S ?T; \text{backtrack} ?T ?W; \text{cdcl}_W\text{-all-struct-inv} ?S \rrbracket \implies \text{backtrack} ?S ?W$

lemma *rtrancpl-skip-backtrack-backtrack-end:*

assumes
*skip: skip^{**} S T and*
bt: backtrack S W and
inv: cdcl_W-all-struct-inv S
shows *backtrack T W*
using *assms*
proof –
have *M-lev: cdcl_W-M-level-inv S*
using *bt inv unfolding cdcl_W-all-struct-inv-def by (auto elim!: backtrack-levE)*
then obtain *k M M1 M2 K i D L N U where*
S: state S = (M, N, U, k, C-Clause (D + {#L#})) and
W: state W = (Propagated L ((D + {#L#})) # M1, N, {#D + {#L#}#} + U,
get-maximum-level D M, C-True) and
decomp: (Marked K (i+1) # M1, M2) ∈ set (get-all-marked-decomposition M) and
lev-l: get-level L M = k and
lev-l-D: get-level L M = get-maximum-level (D+{#L#}) M and
i: i = get-maximum-level D M and
undef: undefined-lit M1 L
using *bt by (elim backtrack-levE) (force simp: cdcl_W-M-level-inv-def)+*
let *?D = (D + {#L#})*

have *[simp]: no-dup (trail S)*
using *M-lev by (auto simp: cdcl_W-M-level-inv-decomp)*
have *cdcl_W-all-struct-inv T*
using *mono-rtrancpl[of skip cdcl_W] by (smt bj cdcl_W-bj.skip inv local.skip other*
rtrancpl-cdcl_W-all-struct-inv-inv)
then have *[simp]: no-dup (trail T)*
unfolding *cdcl_W-all-struct-inv-def cdcl_W-M-level-inv-def by auto*

obtain *MS M_T where M: M = MS @ M_T and M_T: M_T = trail T and nm: ∀ m ∈ set MS. ¬is-marked m*

using *rtrancpl-skip-state-decomp(1)[OF skip] S M-lev by auto*
have *T: state T = (M_T, N, U, k, C-Clause ?D)*
using *M_T rtrancpl-skip-state-decomp(2)[of S T] skip S*
by *(auto simp del: state-simp simp: state-eq-def)*

have *cdcl_W-all-struct-inv T*
apply *(rule rtrancpl-cdcl_W-all-struct-inv-inv[OF - inv])*
using *bj cdcl_W-bj.skip local.skip other rtrancpl-mono[of skip cdcl_W] by blast*
then have *M_T ⊨_{as} CNot ?D*
unfolding *cdcl_W-all-struct-inv-def cdcl_W-conflicting-def using T by blast*
have *∀ L ∈ # ?D. atm-of L ∈ atm-of ‘ lits-of M_T*

proof –

have *f1: ∧ l. ¬ M_T ⊨_a {# – l#} ∨ atm-of l ∈ atm-of ‘ lits-of M_T*
by *(simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set in-lit-of-true-annot*
lits-of-def)
have *∧ l. l ∉ # D ∨ – l ∈ lits-of M_T*

```

    using  $\langle M_T \models_{as} CNot (D + \{\#L\# \}) \rangle$  multi-member-split by fastforce
  then show ?thesis
    using f1 by (meson  $\langle M_T \models_{as} CNot (D + \{\#L\# \}) \rangle$  ball-msetI true-annots-CNot-all-atms-defined)
qed
moreover have no-dup M
  using inv S unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def by auto
ultimately have  $\forall L \in \#?D. atm\text{-}of\ L \notin atm\text{-}of\ 'lits\text{-}of\ MS$ 
  unfolding M unfolding lits-of-def by auto
then have H:  $\bigwedge L. L \in \#?D \implies get\text{-}level\ L\ M = get\text{-}level\ L\ M_T$ 
  unfolding M by (fastforce simp: lits-of-def)
have [simp]: get-maximum-level ?D M = get-maximum-level ?D MT
  by (metis  $\langle M_T \models_{as} CNot (D + \{\#L\# \}) \rangle$  M nm ball-msetI true-annots-CNot-all-atms-defined
    get-maximum-level-skip-un-marked-not-present)

have lev-l': get-level L MT = k
  using lev-l by (auto simp: H)
have [simp]: trail (reduce-trail-to M1 T) = M1
  using T decomp M nm by (smt MT append-assoc beginning-not-marked-invert
    get-all-marked-decomposition-exists-prepend reduce-trail-to-trail-tl-trail-decomp)
have W:  $W \sim cons\text{-}trail (Propagated\ L\ (D + \{\#L\# \})) (reduce\text{-}trail\text{-}to\ M1$ 
  (add-learned-cls (D +  $\{\#L\# \}$ ) (update-backtrack-lvl i (update-conflicting C-True T))))
  using W T i decomp undef by (auto simp del: state-simp simp: state-eq-def)

have lev-l-D': get-level L MT = get-maximum-level (D +  $\{\#L\# \}$ ) MT
  using lev-l-D by (auto simp: H)
have [simp]: get-maximum-level D M = get-maximum-level D MT
proof -
  have  $\bigwedge ms\ m. \neg (ms::('v, nat, 'v\ literal\ multiset)\ marked\text{-}lit\ list) \models_{as} CNot\ m$ 
     $\vee (\forall l \in \#m. atm\text{-}of\ l \in atm\text{-}of\ 'lits\text{-}of\ ms)$ 
    by (simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set in-CNot-implies-uminus(2))
  then have  $\forall l \in \#D. atm\text{-}of\ l \in atm\text{-}of\ 'lits\text{-}of\ M_T$ 
    using  $\langle M_T \models_{as} CNot (D + \{\#L\# \}) \rangle$  by auto
  then show ?thesis
    by (metis M get-maximum-level-skip-un-marked-not-present nm)
qed
then have i': i = get-maximum-level D MT
  using i by auto
have Marked K (i + 1) # M1 ∈ set (map fst (get-all-marked-decomposition M))
  using Set.imageI[OF decomp, of fst] by auto
then have Marked K (i + 1) # M1 ∈ set (map fst (get-all-marked-decomposition MT))
  using fst-get-all-marked-decomposition-prepend-not-marked[OF nm] unfolding M by auto
then obtain M2' where decomp': (Marked K (i+1) # M1, M2') ∈ set (get-all-marked-decomposition
MT)
  by auto
then show backtrack T W
  using backtrack.intros[OF T decomp' lev-l'] lev-l-D' i' W by force
qed

lemma cdclW-bj-decomp-resolve-skip-and-bj:
  assumes cdclW-bj** S T and inv: cdclW-M-level-inv S
  shows (skip-or-resolve** S T
     $\vee (\exists U. skip\text{-}or\text{-}resolve** S U \wedge backtrack\ U\ T))$ 
  using assms
proof induction
  case base

```

```

then show ?case by simp
next
case (step T U) note st = this(1) and bj = this(2) and IH = this(3)
have IH: skip-or-resolve** S T
proof -
  { assume (∃ U. skip-or-resolve** S U ∧ backtrack U T)
    then obtain V where
      bt: backtrack V T and
      skip-or-resolve** S V
      by blast
    have cdclW** S V
      using (skip-or-resolve** S V) rtrancpl-skip-or-resolve-rtrancpl-cdclW by blast
    then have cdclW-M-level-inv V and cdclW-M-level-inv S
      using rtrancpl-cdclW-consistent-inv inv by blast+
    with bj bt have False using backtrack-no-cdclW-bj by simp
  }
  then show ?thesis using IH inv by blast
qed
show ?case
using bj
proof (cases rule: cdclW-bj.cases)
  case backtrack
  then show ?thesis using IH by blast
qed (metis (no-types, lifting) IH rtrancpl.simps)+
qed

lemma resolve-skip-deterministic:
  resolve S T ⟹ skip S U ⟹ False
by fastforce

lemma backtrack-unique:
  assumes
    bt-T: backtrack S T and
    bt-U: backtrack S U and
    inv: cdclW-all-struct-inv S
  shows T ~ U
proof -
  have lev: cdclW-M-level-inv S
  using inv unfolding cdclW-all-struct-inv-def by auto
  then obtain M N U' k D L i K M1 M2 where
    S: state S = (M, N, U', k, C-Clause (D + {#L#})) and
    decomp: (Marked K (i+1) # M1, M2) ∈ set (get-all-marked-decomposition M) and
    get-level L M = k and
    get-level L M = get-maximum-level (D+{#L#}) M and
    get-maximum-level D M = i and
    T: state T = (Propagated L ( (D+{#L#})) # M1 , N, {#D + {#L#}#} + U', i, C-True) and
    undef: undefined-lit M1 L
  using bt-T by (elim backtrack-levE) (force simp: cdclW-M-level-inv-def)+

  obtain D' L' i' K' M1' M2' where
    S': state S = (M, N, U', k, C-Clause (D' + {#L'#})) and
    decomp': (Marked K' (i'+1) # M1', M2') ∈ set (get-all-marked-decomposition M) and
    get-level L' M = k and
    get-level L' M = get-maximum-level (D'+{#L'#}) M and
    get-maximum-level D' M = i' and

```

U : state $U = (\text{Propagated } L' ((D' + \{\#L'\#\})) \# M1', N, \{\#D' + \{\#L'\#\}\# + U', i', C\text{-True})$ and
 undef : undefined-lit $M1' L'$
using $bt\text{-}U \text{ lev } S$ **by** ($\text{elim backtrack-levE}$) ($\text{force simp: cdcl}_W\text{-}M\text{-level-inv-def}$) +
obtain c **where** $M: M = c @ M2 @ \text{Marked } K (i + 1) \# M1$
using decomp **by** auto
obtain c' **where** $M': M = c' @ M2' @ \text{Marked } K' (i' + 1) \# M1'$
using decomp' **by** auto
have $\text{marked: get-all-levels-of-marked } M = \text{rev } [1..<1+k]$
using $\text{inv } S$ **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ $\text{cdcl}_W\text{-}M\text{-level-inv-def}$ **by** auto
then have $i < k$
unfolding M
by ($\text{force simp add: rev-swap[symmetric] dest!: arg-cong[of - - set]$)

have $[simp]: L = L'$
proof (rule ccontr)
assume $\neg ?thesis$
then have $L' \in \# D$
using S **unfolding** S' **by** ($\text{fastforce simp: multiset-eq-iff split: split-if-asm}$)
then have $\text{get-maximum-level } D M \geq k$
using $\langle \text{get-level } L' M = k \rangle$ $\text{get-maximum-level-ge-get-level}$ **by** blast
then show False **using** $\langle \text{get-maximum-level } D M = i \rangle \langle i < k \rangle$ **by** auto
qed
then have $[simp]: D = D'$
using $S S'$ **by** auto
have $[simp]: i=i'$ **using** $\langle \text{get-maximum-level } D' M = i' \rangle \langle \text{get-maximum-level } D M = i \rangle$ **by** auto

Automation in a step later...

have $H: \bigwedge a A B. \text{insert } a A = B \implies a : B$
by blast
have $\text{get-all-levels-of-marked } (c @ M2) = \text{rev } [i+2..<1+k]$ **and**
 $\text{get-all-levels-of-marked } (c' @ M2') = \text{rev } [i+2..<1+k]$
using $\text{marked unfolding } M$
using $\text{marked unfolding } M'$
unfolding $\text{rev-swap[symmetric]}$ **by** ($\text{auto dest: append-cons-eq-upt-length-i-end}$)
from $\text{arg-cong[OF this(1), of set]} \text{arg-cong[OF this(2), of set]}$
have
 $\text{dropWhile } (\lambda L. \neg \text{is-marked } L \vee \text{level-of } L \neq \text{Suc } i) (c @ M2) = []$ **and**
 $\text{dropWhile } (\lambda L. \neg \text{is-marked } L \vee \text{level-of } L \neq \text{Suc } i) (c' @ M2') = []$
unfolding $\text{dropWhile-eq-Nil-conv Ball-def}$
by ($\text{intro allI; case-tac } x; \text{auto dest!: } H \text{ simp add: in-set-conv-decomp}$) +

then have $M1 = M1'$
using $\text{arg-cong[OF } M, \text{ of dropWhile } (\lambda L. \neg \text{is-marked } L \vee \text{level-of } L \neq \text{Suc } i)]$
unfolding M' **by** auto
then show $?thesis$ **using** $T U$ **by** ($\text{auto simp del: state-simp simp: state-eq-def}$)
qed

lemma $\text{if-can-apply-backtrack-no-more-resolve}$:

assumes
 $\text{skip: skip}^{**} S U$ **and**
 $\text{bt: backtrack } S T$ **and**
 $\text{inv: cdcl}_W\text{-all-struct-inv } S$
shows $\neg \text{resolve } U V$
proof (rule ccontr)
assume $\text{resolve: } \neg \neg \text{resolve } U V$

obtain $L\ C\ M\ N\ U'\ k\ D$ **where**
 U : state $U = (\text{Propagated } L\ ((C + \{\#L\#\})) \# M, N, U', k, C\text{-Clause } (D + \{\#-L\#\}))$ **and**
 $\text{get-maximum-level } D\ (\text{Propagated } L\ ((C + \{\#L\#\})) \# M) = k$ **and**
 $\text{state } V = (M, N, U', k, C\text{-Clause } (D \# \cup C))$
using *resolve by auto*
have $\text{cdcl}_W\text{-all-struct-inv } U$
using $\text{mono-rtrancpl}[\text{of skip cdcl}_W]$ **by** (*meson bj cdcl_W-bj.skip inv local.skip other*
rtrancpl-cdcl_W-all-struct-inv-inv)
then have $[\text{iff}]: \text{no-dup } (\text{trail } S)\ \text{cdcl}_W\text{-M-level-inv } S$ **and** $[\text{iff}]: \text{no-dup } (\text{trail } U)$
using $\text{inv unfolding cdcl}_W\text{-all-struct-inv-def cdcl}_W\text{-M-level-inv-def}$ **by** *blast+*
then have
 S : *init-clss* $S = N$
learned-clss $S = U'$
backtrack-lvl $S = k$
conflicting $S = C\text{-Clause } (D + \{\#-L\#\})$
using $\text{rtrancpl-skip-state-decomp}(2)[\text{OF skip}] U$ **by** (*auto simp del: state-simp simp: state-eq-def*)
obtain M_0 **where**
 $\text{tr-S: trail } S = M_0 @ \text{trail } U$ **and**
 $\text{nm: } \forall m \in \text{set } M_0. \neg \text{is-marked } m$
using $\text{rtrancpl-skip-state-decomp}[\text{OF skip}]$ **by** *blast*

obtain $M'\ D'\ L'\ i\ K\ M1\ M2$ **where**
 S' : state $S = (M', N, U', k, C\text{-Clause } (D' + \{\#L'\#\}))$ **and**
 $\text{decomp: } (\text{Marked } K\ (i+1) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } M')$ **and**
 $\text{get-level } L'\ M' = k$ **and**
 $\text{get-level } L'\ M' = \text{get-maximum-level } (D' + \{\#L'\#\})\ M'$ **and**
 $\text{get-maximum-level } D'\ M' = i$ **and**
 $\text{undef: undefined-lit } M1\ L'$ **and**
 T : state $T = (\text{Propagated } L'\ (D' + \{\#L'\#\}) \# M1, N, \{\#D' + \{\#L'\#\}\# + U', i, C\text{-True})$
using $\text{bt } S$ **by** (*force elim!: backtrack-levE*)
obtain c **where** $M: M' = c @ M2 @ \text{Marked } K\ (i + 1) \# M1$
using $\text{get-all-marked-decomposition-exists-prepend}[\text{OF decomp}]$ **by** *auto*
have $\text{marked: get-all-levels-of-marked } M' = \text{rev } [1..<1+k]$
using $\text{inv } S'$ **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def cdcl}_W\text{-M-level-inv-def}$ **by** *auto*
then have $i < k$
unfolding M **by** (*force simp add: rev-swap[symmetric] dest!: arg-cong[of - - set]*)

have $DD': D' + \{\#L'\#\} = D + \{\#-L\#\}$
using $S\ S'$ **by** *auto*
have $[\text{simp}]: L' = -L$
proof (*rule ccontr*)
assume $\neg ?thesis$
then have $-L \in \# D'$
using DD' **by** (*metis add-diff-cancel-right' diff-single-trivial diff-union-swap*
multi-self-add-other-not-self)
moreover
have $M': M' = M_0 @ \text{Propagated } L\ ((C + \{\#L\#\})) \# M$
using $\text{tr-S } U\ S\ S'$ **by** (*auto simp: lits-of-def*)
have $\text{no-dup } M'$
using $\text{inv } U\ S'$ **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def cdcl}_W\text{-M-level-inv-def}$ **by** *auto*
have $\text{atm-L-notin-M: atm-of } L \notin \text{atm-of } '(\text{lits-of } M)$
using $\langle \text{no-dup } M' \rangle M' U\ S\ S'$ **by** (*auto simp: lits-of-def*)
have $\text{get-all-levels-of-marked } M' = \text{rev } [1..<1+k]$
using $\text{inv } U\ S'$ **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def cdcl}_W\text{-M-level-inv-def}$ **by** *auto*

then have *get-all-levels-of-marked* $M = \text{rev } [1..<1+k]$
using $\text{nm } M' S' U$ **by** (*simp add: get-all-levels-of-marked-no-marked*)
then have *get-lev-L*:
get-level L (*Propagated* L ($(C + \{\#L\# \})$) $\# M$) $= k$
using *get-level-get-rev-level-get-all-levels-of-marked* [*OF atm-L-notin-M*,
of [Propagated L ((C + {\#L\#}))]] **by** *simp*
have *atm-of* $L \notin \text{atm-of } \langle \text{lits-of } (\text{rev } M_0) \rangle$
using $\langle \text{no-dup } M' \rangle M' U S'$ **by** (*auto simp: lits-of-def*)
then have *get-level* $L M' = k$
using *get-rev-level-notin-end* [*of L rev M₀ 0*
rev M @ Propagated L ((C + {\#L\#})) # []]
using *tr-S get-lev-L M' U S'* **by** (*simp add: nm lits-of-def*)
ultimately have *get-maximum-level* $D' M' \geq k$
by (*metis get-maximum-level-ge-get-level get-rev-level-uminus*)
then show *False*
using $\langle i < k \rangle$ **unfolding** $\langle \text{get-maximum-level } D' M' = i \rangle$ **by** *auto*
qed
have [*simp*]: $D = D'$ **using** DD' **by** *auto*
have $\text{cdcl}_W^{**} S U$
using *bj cdcl_W-bj.skip local.skip mono-rtranclp* [*of skip cdcl_W S U*] **other by** *meson*
then have *cdcl_W-all-struct-inv U*
using *inv rtranclp-cdcl_W-all-struct-inv-inv* **by** *blast*
then have *Propagated L ((C + {\#L\#})) # M* $\models_{\text{as}} \text{CNot } (D' + \{\#L'\# \})$
using *cdcl_W-all-struct-inv-def cdcl_W-conflicting-def U* **by** *auto*
then have $\forall L' \in \#D. \text{atm-of } L' \in \text{atm-of } \langle \text{lits-of } (\text{Propagated } L ((C + \{\#L\# \})) \# M) \rangle$
by (*metis CNot-plus CNot-singleton Un-insert-right* $\langle D = D' \rangle$ *true-annots-insert ball-msetI*
atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set in-CNot-implies-uminus(2)
sup-bot.comm-neutral)
then have *get-maximum-level* $D M' = k$
using *tr-S nm U S'*
get-maximum-level-skip-un-marked-not-present [*of D*
Propagated L ((C + {\#L\#})) # M M₀]
unfolding $\langle \text{get-maximum-level } D (\text{Propagated } L ((C + \{\#L\# \})) \# M) = k \rangle$
unfolding $\langle D = D' \rangle$
by *simp*
show *False*
using $\langle \text{get-maximum-level } D' M' = i \rangle \langle \text{get-maximum-level } D M' = k \rangle \langle i < k \rangle$ **by** *auto*
qed

lemma *if-can-apply-resolve-no-more-backtrack*:

assumes
*skip: skip^{**} S U* **and**
resolve: resolve S T **and**
inv: cdcl_W-all-struct-inv S
shows $\neg \text{backtrack } U V$
using *assms*
by (*meson if-can-apply-backtrack-no-more-resolve rtranclp.rtrancl-refl*
rtranclp-skip-backtrack-backtrack)

lemma *if-can-apply-backtrack-skip-or-resolve-is-skip*:

assumes
bt: backtrack S T **and**
*skip: skip-or-resolve^{**} S U* **and**
inv: cdcl_W-all-struct-inv S
shows *skip^{**} S U*


```

using assms(2,3,1)
by induction (simp-all add: if-can-apply-backtrack-no-more-resolve)

lemma cdclW-bj-bj-decomp:
assumes cdclW-bj** S W and cdclW-all-struct-inv S
shows
  (∃ T U V. (λS T. skip-or-resolve S T ∧ no-step backtrack S)** S T
    ∧ (λT U. resolve T U ∧ no-step backtrack T) T U
    ∧ skip** U V ∧ backtrack V W)
  ∨ (∃ T U. (λS T. skip-or-resolve S T ∧ no-step backtrack S)** S T
    ∧ (λT U. resolve T U ∧ no-step backtrack T) T U ∧ skip** U W)
  ∨ (∃ T. skip** S T ∧ backtrack T W)
  ∨ skip** S W (is ?RB S W ∨ ?R S W ∨ ?SB S W ∨ ?S S W)
using assms
proof induction
case base
then show ?case by simp
next
case (step W X) note st = this(1) and bj = this(2) and IH = this(3)[OF this(4)] and inv = this(4)

have ¬?RB S W and ¬?SB S W
proof (clarify, goal-cases)
case (1 T U V)
have skip-or-resolve** S T
using 1(1) by (auto dest!: rtrancpl-and-rtrancpl-left)
then show False
by (metis (no-types, lifting) 1(2) 1(4) 1(5) backtrack-no-cdclW-bj
cdclW-all-struct-inv-def cdclW-all-struct-inv-inv cdclW-o.bj local.bj other
resolve rtrancpl-cdclW-all-struct-inv-inv rtrancpl-skip-backtrack-backtrack
rtrancpl-skip-or-resolve-rtrancpl-cdclW step.prem)
next
case 2
then show ?case by (meson assms(2) cdclW-all-struct-inv-def backtrack-no-cdclW-bj
local.bj rtrancpl-skip-backtrack-backtrack)
qed
then have IH: ?R S W ∨ ?S S W using IH by blast

have cdclW** S W by (metis cdclW-o.bj mono-rtrancpl other st)
then have inv-W: cdclW-all-struct-inv W by (simp add: rtrancpl-cdclW-all-struct-inv-inv
step.prem)
consider
  (BT) X' where backtrack W X'
  | (skip) no-step backtrack W and skip W X
  | (resolve) no-step backtrack W and resolve W X
using bj cdclW-bj.cases by meson
then show ?case
proof cases
case (BT X')
then consider
  (bt) backtrack W X
  | (sk) skip W X
using bj if-can-apply-backtrack-no-more-resolve[of W W X' X] inv-W cdclW-bj.cases by fast
then show ?thesis
proof cases
case bt

```

```

    then show ?thesis using IH by auto
  next
    case sk
    then show ?thesis using IH by (meson rtrancpl-trans r-into-rtrancpl)
  qed
next
case skip
then show ?thesis using IH by (meson rtrancpl.rtrancpl-into-rtrancpl)
next
case resolve note no-bt = this(1) and res = this(2)
consider
  (RS) T U where
    ( $\lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S$ )** S T and
    resolve T U and
    no-step backtrack T and
    skip** U W
  | (S) skip** S W
using IH by auto
then show ?thesis
proof cases
case (RS T U)
have cdclW** S T
  using RS(1) cdclW-bj.resolve cdclW-o.bj other skip
  mono-rtrancpl[of ( $\lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S$ ) cdclW S T]
  by meson
then have cdclW-all-struct-inv U
  by (meson RS(2) cdclW-all-struct-inv-inv cdclW-bj.resolve cdclW-o.bj other
    rtrancpl-cdclW-all-struct-inv-inv step.prem)
{ fix U'
  assume skip** U U' and skip** U' W
  have cdclW-all-struct-inv U'
    using  $\langle \text{cdcl}_W\text{-all-struct-inv } U \rangle \langle \text{skip}^{**} U U' \rangle$  rtrancpl-cdclW-all-struct-inv-inv
    cdclW-o.bj rtrancpl-mono[of skip cdclW] other skip by blast
  then have no-step backtrack U'
    using if-can-apply-backtrack-no-more-resolve[OF  $\langle \text{skip}^{**} U' W \rangle$ ] res by blast
}
with  $\langle \text{skip}^{**} U W \rangle$ 
have ( $\lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S$ )** U W
proof induction
case base
then show ?case by simp
next
case (step V W) note st = this(1) and skip = this(2) and IH = this(3) and H = this(4)
have  $\bigwedge U'. \text{skip}^{**} U' V \implies \text{skip}^{**} U' W$ 
  using skip by auto
then have ( $\lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S$ )** U V
  using IH H by blast
moreover have ( $\lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S$ )** V W
  by (simp add: local.skip r-into-rtrancpl st step.prem)
ultimately show ?case by simp
qed
then show ?thesis
proof -
  have f1:  $\forall p \text{ pa pb pc. } \neg p \text{ (pa) pb} \vee \neg p^{**} \text{ pb pc} \vee p^{**} \text{ pa pc}$ 

```

```

    by (meson converse-rtrancpl-into-rtrancpl)
  have skip-or-resolve T U  $\wedge$  no-step backtrack T
    using RS(2) RS(3) by force
  then have ( $\lambda p$  pa. skip-or-resolve p pa  $\wedge$  no-step backtrack p)** T W
    proof -
      have ( $\exists$  vr19 vr16 vr17 vr18. vr19 (vr16::'st) vr17  $\wedge$  vr19** vr17 vr18
         $\wedge$   $\neg$  vr19** vr16 vr18)
         $\vee$   $\neg$  (skip-or-resolve T U  $\wedge$  no-step backtrack T)
         $\vee$   $\neg$  ( $\lambda uu$  uua. skip-or-resolve uu uua  $\wedge$  no-step backtrack uu)** U W
         $\vee$  ( $\lambda uu$  uua. skip-or-resolve uu uua  $\wedge$  no-step backtrack uu)** T W
      by force
    then show ?thesis
      by (metis (no-types)  $\langle \lambda S$  T. skip-or-resolve S T  $\wedge$  no-step backtrack S)** U W  $\rangle$ 
         $\langle$  skip-or-resolve T U  $\wedge$  no-step backtrack T  $\rangle$  f1)
    qed
  then have ( $\lambda p$  pa. skip-or-resolve p pa  $\wedge$  no-step backtrack p)** S W
    using RS(1) by force
  then show ?thesis
    using no-bt res by blast
  qed
next
case S
{ fix U'
  assume skip** S U' and skip** U' W
  then have cdclW** S U'
    using mono-rtrancpl[of skip cdclW S U'] by (simp add: cdclW-o.bj other skip)
  then have cdclW-all-struct-inv U'
    by (metis (no-types, hide-lams)  $\langle$  cdclW-all-struct-inv S  $\rangle$  rtrancpl-cdclW-all-struct-inv-inv)
  then have no-step backtrack U'
    using if-can-apply-backtrack-no-more-resolve[OF  $\langle$  skip** U' W  $\rangle$ ] res by blast
}
with S
have ( $\lambda S$  T. skip-or-resolve S T  $\wedge$  no-step backtrack S)** S W
  proof induction
    case base
    then show ?case by simp
  next
  case (step V W) note st = this(1) and skip = this(2) and IH = this(3) and H = this(4)
  have  $\bigwedge U'. \text{skip** } U' V \implies \text{skip** } U' W$ 
    using skip by auto
  then have ( $\lambda S$  T. skip-or-resolve S T  $\wedge$  no-step backtrack S)** S V
    using IH H by blast
  moreover have ( $\lambda S$  T. skip-or-resolve S T  $\wedge$  no-step backtrack S)** V W
    by (simp add: local.skip r-into-rtrancpl st step.prem)
  ultimately show ?case by simp
  qed
  then show ?thesis using res no-bt by blast
  qed
qed
qed

```

Backjumping is confluent lemma *cdcl_W-bj-state-eq-compatible*:

assumes

cdcl_W-bj S T and *cdcl_W-M-level-inv* S

$S \sim S'$ and
 $T \sim T'$
shows $cdcl_W\text{-bj } S' T'$
using *assms*
by *induction* (*auto*
intro: skip-state-eq-compatible backtrack-state-eq-compatible resolve-state-eq-compatible)

lemma *trancpl-cdcl_W-bj-state-eq-compatible*:
assumes
 $cdcl_W\text{-bj}^{++} S T$ and $inv: cdcl_W\text{-M-level-inv } S$ and
 $S \sim S'$ and
 $T \sim T'$
shows $cdcl_W\text{-bj}^{++} S' T'$
using *assms*
proof (*induction arbitrary: S' T'*)
case *base*
then show *?case*
using *cdcl_W-bj-state-eq-compatible* **by** *blast*
next
case (*step T U*) **note** $IH = this(3)[OF\ this(4-5)]$
have $cdcl_W^{++} S T$
using *trancpl-mono*[*of cdcl_W-bj cdcl_W*] *other step.hyps(1)* **by** *blast*
then have $cdcl_W\text{-M-level-inv } T$
using *inv trancpl-cdcl_W-consistent-inv* **by** *blast*
then have $cdcl_W\text{-bj}^{++} T T'$
using $\langle U \sim T' \rangle cdcl_W\text{-bj-state-eq-compatible}[of\ T\ U]\ \langle cdcl_W\text{-bj } T\ U \rangle$ **by** *auto*
then show *?case*
using $IH[of\ T]$ **by** *auto*
qed

The case distinction is needed, since $T \sim V$ does not imply that $R^{**} T V$.

lemma *cdcl_W-bj-strongly-confluent*:
assumes
 $cdcl_W\text{-bj}^{**} S V$ and
 $cdcl_W\text{-bj}^{**} S T$ and
 $n\text{-s: no-step } cdcl_W\text{-bj } V$ and
 $inv: cdcl_W\text{-all-struct-inv } S$
shows $T \sim V \vee cdcl_W\text{-bj}^{**} T V$
using *assms(2)*
proof *induction*
case *base*
then show *?case* **by** (*simp add: assms(1)*)
next
case (*step T U*) **note** $st = this(1)$ and $s\text{-o-r} = this(2)$ and $IH = this(3)$
have $cdcl_W^{**} S T$
using *st mono-rtrancpl*[*of cdcl_W-bj cdcl_W*] *other* **by** *blast*
then have $lev\text{-}T: cdcl_W\text{-M-level-inv } T$
using *inv rtrancpl-cdcl_W-consistent-inv*[*of S T*]
unfolding *cdcl_W-all-struct-inv-def* **by** *auto*

consider
 $(TV)\ T \sim V$
 $| (bj\text{-}TV)\ cdcl_W\text{-bj}^{**} T V$
using IH **by** *blast*
then show *?case*

```

proof cases
  case  $TV$ 
  have  $no\text{-}step\ cdcl_W\text{-}bj\ T$ 
    using  $\langle cdcl_W\text{-}M\text{-}level\text{-}inv\ T \rangle\ n\text{-}s\ cdcl_W\text{-}bj\text{-}state\text{-}eq\text{-}compatible[of\ T - V]\ TV$  by auto
  then show  $?thesis$ 
    using  $s\text{-}o\text{-}r$  by auto
next
  case  $bj\text{-}TV$ 
  then obtain  $U'$  where
     $T\text{-}U': cdcl_W\text{-}bj\ T\ U'$  and
     $cdcl_W\text{-}bj^{**}\ U'\ V$ 
    using  $IH\ n\text{-}s\ s\text{-}o\text{-}r$  by (metis rtranclp-unfold tranclpD)
  have  $cdcl_W^{**}\ S\ T$ 
    by (metis (no-types, hide-lams) bj mono-rtranclp[of cdcl_W-bj cdcl_W] other st)
  then have  $inv\text{-}T: cdcl_W\text{-}all\text{-}struct\text{-}inv\ T$ 
    by (metis (no-types, hide-lams) inv rtranclp-cdcl_W-all-struct-inv-inv)

  have  $lev\text{-}U: cdcl_W\text{-}M\text{-}level\text{-}inv\ U$ 
    using  $s\text{-}o\text{-}r\ cdcl_W\text{-}consistent\text{-}inv\ lev\text{-}T\ other$  by blast
  show  $?thesis$ 
    using  $s\text{-}o\text{-}r$ 
    proof cases
      case backtrack
      then obtain  $V0$  where  $skip^{**}\ T\ V0$  and backtrack  $V0\ V$ 
        using  $IH\ if\text{-}can\text{-}apply\text{-}backtrack\text{-}skip\text{-}or\text{-}resolve\text{-}is\text{-}skip[OF\ backtrack - inv\text{-}T]$ 
         $cdcl_W\text{-}bj\text{-}decomp\text{-}resolve\text{-}skip\text{-}and\text{-}bj$ 
        by (meson bj-TV cdcl_W-bj.backtrack inv-T lev-T n-s
          rtranclp-skip-backtrack-backtrack-end)
      then have  $cdcl_W\text{-}bj^{**}\ T\ V0$  and  $cdcl_W\text{-}bj\ V0\ V$ 
        using  $rtranclp\text{-}mono[of\ skip\ cdcl_W\text{-}bj]$  by blast+
      then show  $?thesis$ 
        using  $\langle backtrack\ V0\ V \rangle\ \langle skip^{**}\ T\ V0 \rangle\ backtrack\text{-}unique\ inv\text{-}T\ local.backtrack$ 
         $rtranclp\text{-}skip\text{-}backtrack\text{-}backtrack$  by auto
      next
      case resolve
      then have  $U \sim U'$ 
        by (meson T-U' cdcl_W-bj.simps if-can-apply-backtrack-no-more-resolve inv-T
          resolve-skip-deterministic resolve-unique rtranclp.rtrancl-refl)
      then show  $?thesis$ 
        using  $\langle cdcl_W\text{-}bj^{**}\ U'\ V \rangle$  unfolding  $rtranclp\text{-}unfold$ 
        by (meson T-U' bj cdcl_W-consistent-inv lev-T other state-eq-ref state-eq-sym
          tranclp-cdcl_W-bj-state-eq-compatible)
      next
      case skip
      consider
         $(sk)\ skip\ T\ U'$ 
         $| (bt)\ backtrack\ T\ U'$ 
        using  $T\text{-}U'$  by (meson cdcl_W-bj.cases local.skip resolve-skip-deterministic)
      then show  $?thesis$ 
        proof cases
          case sk
          then show  $?thesis$ 
            using  $\langle cdcl_W\text{-}bj^{**}\ U'\ V \rangle$  unfolding  $rtranclp\text{-}unfold$ 
            by (meson T-U' bj cdcl_W-all-inv(3) cdcl_W-all-struct-inv-def inv-T local.skip other
              tranclp-cdcl_W-bj-state-eq-compatible skip-unique state-eq-ref)

```

```

next
  case bt
  have skip++ T U
    using local.skip by blast
  then show ?thesis
    using bt by (metis  $\langle \text{cdcl}_W\text{-bj}^{**} \ U' \ V \rangle$  backtrack inv-T tranclp-unfold-begin
      rtranclp-skip-backtrack-backtrack-end tranclp-into-rtranclp)
  qed
qed
qed
qed

```

lemma *cdcl_W-bj-unique-normal-form*:

```

assumes
  ST: cdclW-bj** S T and SU: cdclW-bj** S U and
  n-s-U: no-step cdclW-bj U and
  n-s-T: no-step cdclW-bj T and
  inv: cdclW-all-struct-inv S
shows T ~ U
proof -
  have T ~ U  $\vee$  cdclW-bj** T U
    using ST SU cdclW-bj-strongly-confluent inv n-s-U by blast
  then show ?thesis
    by (metis (no-types) n-s-T rtranclp-unfold state-eq-ref tranclp-unfold-begin)
qed

```

lemma *full-cdcl_W-bj-unique-normal-form*:

```

assumes full cdclW-bj S T and full cdclW-bj S U and
  inv: cdclW-all-struct-inv S
shows T ~ U
  using cdclW-bj-unique-normal-form assms unfolding full-def by blast

```

19.3 CDCL FW

inductive *cdcl_W-merge-restart* :: '*st* \Rightarrow '*st* \Rightarrow bool **where**
fw-r-propagate: *propagate S S'* \Longrightarrow *cdcl_W-merge-restart S S'* |
fw-r-conflict: *conflict S T* \Longrightarrow *full cdcl_W-bj T U* \Longrightarrow *cdcl_W-merge-restart S U* |
fw-r-decide: *decide S S'* \Longrightarrow *cdcl_W-merge-restart S S'* |
fw-r-rf: *cdcl_W-rf S S'* \Longrightarrow *cdcl_W-merge-restart S S'*

lemma *cdcl_W-merge-restart-cdcl_W*:

```

assumes cdclW-merge-restart S T
shows cdclW** S T
using assms
proof induction
  case (fw-r-conflict S T U) note confl = this(1) and bj = this(2)
  have cdclW S T using confl by (simp add: cdclW.intros r-into-rtranclp)
  moreover
    have cdclW-bj** T U using bj unfolding full-def by auto
    then have cdclW** T U by (metis cdclW-o.bj mono-rtranclp other)
  ultimately show ?case by auto
qed (simp-all add: cdclW-o.intros cdclW.intros r-into-rtranclp)

```

lemma *cdcl_W-merge-restart-conflicting-true-or-no-step*:

```

assumes cdclW-merge-restart S T

```

```

shows conflicting  $T = C\text{-True} \vee \text{no-step } \text{cdcl}_W \ T$ 
using assms
proof induction
case (fw-r-conflict  $S \ T \ U$ ) note confl = this(1) and n-s = this(2)
{ fix  $D \ V$ 
  assume  $\text{cdcl}_W \ U \ V$  and conflicting  $U = C\text{-Clause } D$ 
  then have False
    using n-s unfolding full-def
    by (induction rule:  $\text{cdcl}_W\text{-all-rules-induct}$ ) (auto dest!:  $\text{cdcl}_W\text{-bj.intros}$  )
  }
then show ?case by (cases conflicting  $U$ ) fastforce+
qed (auto simp add:  $\text{cdcl}_W\text{-rf.simps}$ )

inductive  $\text{cdcl}_W\text{-merge} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$  where
fw-propagate:  $\text{propagate } S \ S' \Longrightarrow \text{cdcl}_W\text{-merge } S \ S' \mid$ 
fw-conflict:  $\text{conflict } S \ T \Longrightarrow \text{full } \text{cdcl}_W\text{-bj } T \ U \Longrightarrow \text{cdcl}_W\text{-merge } S \ U \mid$ 
fw-decide:  $\text{decide } S \ S' \Longrightarrow \text{cdcl}_W\text{-merge } S \ S' \mid$ 
fw-forget:  $\text{forget } S \ S' \Longrightarrow \text{cdcl}_W\text{-merge } S \ S'$ 

lemma  $\text{cdcl}_W\text{-merge-cdcl}_W\text{-merge-restart}$ :
 $\text{cdcl}_W\text{-merge } S \ T \Longrightarrow \text{cdcl}_W\text{-merge-restart } S \ T$ 
by (meson  $\text{cdcl}_W\text{-merge.cases } \text{cdcl}_W\text{-merge-restart.simps}$  forget)

lemma  $\text{rtrancpl-cdcl}_W\text{-merge-rtrancpl-cdcl}_W\text{-merge-restart}$ :
 $\text{cdcl}_W\text{-merge}^{**} S \ T \Longrightarrow \text{cdcl}_W\text{-merge-restart}^{**} S \ T$ 
using  $\text{rtrancpl-mono[of } \text{cdcl}_W\text{-merge } \text{cdcl}_W\text{-merge-restart]}$   $\text{cdcl}_W\text{-merge-cdcl}_W\text{-merge-restart}$  by blast

lemma  $\text{cdcl}_W\text{-merge-rtrancpl-cdcl}_W$ :
 $\text{cdcl}_W\text{-merge } S \ T \Longrightarrow \text{cdcl}_W^{**} S \ T$ 
using  $\text{cdcl}_W\text{-merge-cdcl}_W\text{-merge-restart } \text{cdcl}_W\text{-merge-restart-cdcl}_W$  by blast

lemma  $\text{rtrancpl-cdcl}_W\text{-merge-rtrancpl-cdcl}_W$ :
 $\text{cdcl}_W\text{-merge}^{**} S \ T \Longrightarrow \text{cdcl}_W^{**} S \ T$ 
using  $\text{rtrancpl-mono[of } \text{cdcl}_W\text{-merge } \text{cdcl}_W^{**}]$   $\text{cdcl}_W\text{-merge-rtrancpl-cdcl}_W$  by auto

lemmas  $\text{trail-reduce-trail-to}_{NOT}\text{-add-cl}_{NOT}\text{-unfolded[simp]} =$ 
 $\text{trail-reduce-trail-to}_{NOT}\text{-add-cl}_{NOT}\text{[unfolded o-def]}$ 

lemma  $\text{trail}_W\text{-eq-reduce-trail-to}_{NOT}\text{-eq}$ :
 $\text{trail } S = \text{trail } T \Longrightarrow \text{trail } (\text{reduce-trail-to}_{NOT} \ F \ S) = \text{trail } (\text{reduce-trail-to}_{NOT} \ F \ T)$ 
proof (induction  $F \ S$  arbitrary:  $T$  rule:  $\text{reduce-trail-to}_{NOT}\text{.induct}$ )
case (1  $F \ S \ T$ ) note IH = this(1) and tr = this(2)
then have  $\square = \text{convert-trail-from-}W \ (\text{trail } S)$ 
 $\vee \text{length } F = \text{length } (\text{convert-trail-from-}W \ (\text{trail } S))$ 
 $\vee \text{trail } (\text{reduce-trail-to}_{NOT} \ F \ (\text{tl-trail } S)) = \text{trail } (\text{reduce-trail-to}_{NOT} \ F \ (\text{tl-trail } T))$ 
using IH by (metis (no-types) comp-apply trail-tl-trail)
then show  $\text{trail } (\text{reduce-trail-to}_{NOT} \ F \ S) = \text{trail } (\text{reduce-trail-to}_{NOT} \ F \ T)$ 
using tr by (metis (no-types) comp-apply  $\text{reduce-trail-to}_{NOT}\text{.elims}$ )
qed

lemma  $\text{trail-reduce-trail-to}_{NOT}\text{-add-learned-cl}_{NOT}\text{[simp]}$ :
 $\text{no-dup } (\text{trail } S) \Longrightarrow$ 
 $\text{trail } (\text{reduce-trail-to}_{NOT} \ M \ (\text{add-learned-cl}_{NOT} \ D \ S)) = \text{trail } (\text{reduce-trail-to}_{NOT} \ M \ S)$ 
by (rule  $\text{trail}_W\text{-eq-reduce-trail-to}_{NOT}\text{-eq}$ ) simp

```

```

lemma reduce-trail-toNOT-reduce-trail-convert:
  reduce-trail-toNOT C S = reduce-trail-to (convert-trail-from-NOT C) S
apply (induction C S rule: reduce-trail-toNOT.induct)
apply (subst reduce-trail-toNOT.simps, subst reduce-trail-to.simps)
by (auto simp: comp-def)

lemma reduce-trail-to-length:
  length M = length M'  $\implies$  reduce-trail-to M S = reduce-trail-to M' S
apply (induction M S arbitrary: rule: reduce-trail-to.induct)
apply (case-tac trail S  $\neq$  [] ; case-tac length (trail S)  $\neq$  length M'; simp)
by (simp-all add: reduce-trail-to-length-ne)

lemma cdclW-merge-is-cdclNOT-merged-bj-learn:
assumes
  inv: cdclW-all-struct-inv S and
  cdclW:cdclW-merge S T
shows cdclNOT-merged-bj-learn S T
   $\vee$  (no-step cdclW-merge T  $\wedge$  conflicting T  $\neq$  C-True)
using cdclW inv
proof induction
case (fw-propagate S T) note propa = this(1)
then obtain M N U k L C where
  H: state S = (M, N, U, k, C-True) and
  CL: C + {#L#}  $\in$  # clauses S and
  M-C: M  $\models_{as}$  CNot C and
  undef: undefined-lit (trail S) L and
  T: T  $\sim$  cons-trail (Propagated L (C + {#L#})) S
using propa by auto
have propagateNOT S T
apply (rule propagateNOT.propagateNOT[of - C L])
using H CL T undef M-C by (auto simp: state-eqNOT-def state-eq-def clauses-def
  simp del: state-simpNOT state-simp)
then show ?case
using cdclNOT-merged-bj-learn.intros(2) by blast
next
case (fw-decide S T) note dec = this(1) and inv = this(2)
then obtain L where
  undef-L: undefined-lit (trail S) L and
  atm-L: atm-of L  $\in$  atms-of-msu (init-clss S) and
  T: T  $\sim$  cons-trail (Marked L (Suc (backtrack-lvl S)))
  (update-backtrack-lvl (Suc (backtrack-lvl S)) S)
by auto
have decideNOT S T
apply (rule decideNOT.decideNOT)
using undef-L apply simp
using atm-L inv unfolding cdclW-all-struct-inv-def no-strange-atm-def clauses-def apply auto[]
using T undef-L unfolding state-eq-def state-eqNOT-def by (auto simp: clauses-def)
then show ?case using cdclNOT-merged-bj-learn-decideNOT by blast
next
case (fw-forget S T) note rf = this(1) and inv = this(2)
then obtain M N C U k where
  S: state S = (M, N, {#C#} + U, k, C-True) and
   $\neg$  M  $\models_{asm}$  clauses S and
  C  $\notin$  set (get-all-mark-of-propagated (trail S)) and

```



```

  C-init:  $C \notin \# \text{ init-clss } S$  and
  C-le:  $C \in \# \text{ learned-clss } S$  and
  T:  $T \sim \text{remove-clss } C \ S$ 
  by auto
have init-clss  $S \models_{pm} C$ 
  using inv C-le unfolding cdclW-all-struct-inv-def cdclW-learned-clause-def
  by (meson mem-set-mset-iff true-clss-clss-in-imp-true-clss-clss)
then have S-C: clauses  $S - \text{replicate-mset } (\text{count } (\text{clauses } S) \ C) \ C \models_{pm} C$ 
  using C-le C-init unfolding clauses-def by (simp add: Un-Diff)
moreover have H: init-clss  $S + (\text{learned-clss } S - \text{replicate-mset } (\text{count } (\text{learned-clss } S) \ C) \ C)$ 
  = init-clss  $S + \text{learned-clss } S - \text{replicate-mset } (\text{count } (\text{learned-clss } S) \ C) \ C$ 
  using C-le C-init by (metis clauses-def clauses-remove-clss diff-zero gr0I
    init-clss-remove-clss learned-clss-remove-clss plus-multiset.rep-eq replicate-mset-0
    semiring-normalization-rules(5))
have forgetNOT  $S \ T$ 
  apply (rule forgetNOT.forgetNOT)
  using S-C apply blast
  using S apply simp
  using  $\langle C \in \# \text{ learned-clss } S \rangle$  apply (simp add: clauses-def)
  using T C-le C-init by (auto
    simp: state-eq-def Un-Diff state-eqNOT-def clauses-def ac-simps H
    simp del: state-simp state-simpNOT)
then show ?case using cdclNOT-merged-bj-learn-forgetNOT by blast
next
case (fw-conflict  $S \ T \ U$ ) note confl = this(1) and bj = this(2) and inv = this(3)
obtain  $C_S$  where
  confl-T: conflicting  $T = C\text{-Clause } C_S$  and
   $C_S$ :  $C_S \in \# \text{ clauses } S$  and
  tr-S- $C_S$ : trail  $S \models_{as} C\text{Not } C_S$ 
  using confl by auto
have cdclW-all-struct-inv  $T$ 
  using cdclW.simps cdclW-all-struct-inv-inv confl inv by blast
then have cdclW-M-level-inv  $T$ 
  unfolding cdclW-all-struct-inv-def by auto
then consider
  (no-bt) skip-or-resolve**  $T \ U$ 
  | (bt)  $T' \ \text{where } \text{skip-or-resolve** } T \ T' \ \text{and } \text{backtrack } T' \ U$ 
  using bj rtrancplp-cdclW-bj-skip-or-resolve-backtrack unfolding full-def by meson
then show ?case
proof cases
  case no-bt
  then have conflicting  $U \neq C\text{-True}$ 
    using confl by (induction rule: rtrancplp-induct) auto
  moreover then have no-step cdclW-merge  $U$ 
    by (auto simp: cdclW-merge.simps)
  ultimately show ?thesis by blast
next
  case bt note s-or-r = this(1) and bt = this(2)
  have cdclW**  $T \ T'$ 
    using s-or-r mono-rtrancplp[of skip-or-resolve cdclW] rtrancplp-skip-or-resolve-rtrancplp-cdclW
    by blast
  then have cdclW-M-level-inv  $T'$ 
    using rtrancplp-cdclW-consistent-inv  $\langle \text{cdcl}_W\text{-M-level-inv } T \rangle$  by blast
  then obtain  $M1 \ M2 \ i \ D \ L \ K$  where
    confl-T': conflicting  $T' = C\text{-Clause } (D + \{\#L\# \})$  and

```

```

M1-M2:(Marked K (i+1) # M1, M2) ∈ set (get-all-marked-decomposition (trail T')) and
get-level L (trail T') = backtrack-lvl T' and
get-level L (trail T') = get-maximum-level (D+{#L#}) (trail T') and
get-maximum-level D (trail T') = i and
undef-L: undefined-lit M1 L and
U: U ~ cons-trail (Propagated L (D+{#L#}))
    (reduce-trail-to M1
      (add-learned-cls (D + {#L#})
        (update-backtrack-lvl i
          (update-conflicting C-True T')))))
using bt by (auto elim: backtrack-levE)
have [simp]: clauses S = clauses T
using confl by auto
have [simp]: clauses T = clauses T'
using s-or-r
proof (induction)
  case base
  then show ?case by simp
next
  case (step U V) note st = this(1) and s-o-r = this(2) and IH = this(3)
  have clauses U = clauses V
  using s-o-r by auto
  then show ?case using IH by auto
qed
have inv-T: cdclW-all-struct-inv T
  by (meson cdclW-cp.simps confl inv r-into-rtrancplp rtrancplp-cdclW-all-struct-inv-inv
    rtrancplp-cdclW-cp-rtrancplp-cdclW)
have cdclW** T T'
  using rtrancplp-skip-or-resolve-rtrancplp-cdclW s-or-r by blast
have inv-T': cdclW-all-struct-inv T'
  using (cdclW** T T') inv-T rtrancplp-cdclW-all-struct-inv-inv by blast
have inv-U: cdclW-all-struct-inv U
  using cdclW-merge-restart-cdclW confl fw-r-conflict inv local.bj
  rtrancplp-cdclW-all-struct-inv-inv by blast

have [simp]: init-clss S = init-clss T'
  using (cdclW** T T') cdclW-init-clss confl cdclW-all-struct-inv-def conflict inv
  by (metis (cdclW-M-level-inv T) rtrancplp-cdclW-init-clss)
then have atm-L: atm-of L ∈ atms-of-msu (clauses S)
  using inv-T' confl-T' unfolding cdclW-all-struct-inv-def no-strange-atm-def clauses-def
  by auto
obtain M where tr-T: trail T = M @ trail T'
  using s-or-r by (induction rule: rtrancplp-induct) auto
obtain M' where
  tr-T': trail T' = M' @ Marked K (i+1) # tl (trail U) and
  tr-U: trail U = Propagated L (D + {#L#}) # tl (trail U)
  using U M1-M2 undef-L inv-T' unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def
  by auto
def M'' ≡ M @ M'
  have tr-T: trail S = M'' @ Marked K (i+1) # tl (trail U)
  using tr-T tr-T' confl unfolding M''-def by auto
have init-clss T' + learned-clss S ⊨pm D + {#L#}
  using inv-T' confl-T' unfolding cdclW-all-struct-inv-def cdclW-learned-clause-def clauses-def
  by simp
have reduce-trail-to (convert-trail-from-NOT (convert-trail-from-W M1)) S =

```

```

    reduce-trail-to M1 S
  by (rule reduce-trail-to-length) simp
moreover have trail (reduce-trail-to M1 S) = M1
  apply (rule reduce-trail-to-skip-beginning[of - M @ - @ M2 @ [Marked K (Suc i)]])
  using confl M1-M2 (trail T = M @ trail T')
  apply (auto dest!: get-all-marked-decomposition-exists-prepend
    elim!: conflictE)
  by (rule sym) auto
ultimately have [simp]: trail (reduce-trail-toNOT (convert-trail-from-W M1) S) = M1
  using M1-M2 confl by (auto simp add: reduce-trail-toNOT-reduce-trail-convert)
have every-mark-is-a-conflict U
  using inv-U unfolding cdclW-all-struct-inv-def cdclW-conflicting-def by simp
then have tl (trail U)  $\models_{as}$  CNot D
  by (metis add-diff-cancel-left' append-self-conv2 tr-U union-commute)
have backjump-l S U
  apply (rule backjump-l[of - - - - L])
  using tr-T apply simp
  using inv unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def apply simp
  using U M1-M2 confl undef-L M1-M2 inv-T' inv unfolding cdclW-all-struct-inv-def
    cdclW-M-level-inv-def apply (auto simp: state-eqNOT-def simp del: state-simpNOT)[]
  using CS apply simp
  using tr-S-CS apply simp

  using U undef-L M1-M2 inv-T' inv unfolding cdclW-all-struct-inv-def
    cdclW-M-level-inv-def apply auto[]
  using undef-L atm-L apply simp
  using (init-cls T' + learned-cls S  $\models_{pm}$  D + {#L#}) unfolding clauses-def apply simp
  apply (metis (tl (trail U)  $\models_{as}$  CNot D) convert-trail-from-W-tl
    convert-trail-from-W-true-annots)
  using inv-T' inv-U U confl-T' undef-L M1-M2 unfolding cdclW-all-struct-inv-def
    distinct-cdclW-state-def by (simp add: cdclW-M-level-inv-decomp)
  then show ?thesis using cdclNOT-merged-bj-learn-backjump-l by fast
qed
qed

```

abbreviation $cdcl_{NOT}\text{-restart}$ **where**

$cdcl_{NOT}\text{-restart} \equiv restart\text{-ops}.cdcl_{NOT}\text{-raw-restart } cdcl_{NOT} \text{ restart}$

lemma $cdcl_W\text{-merge-restart-is-cdcl}_{NOT}\text{-merged-bj-learn-restart-no-step}$:

assumes

$inv: cdcl_W\text{-all-struct-inv } S$ **and**

$cdcl_W: cdcl_W\text{-merge-restart } S \ T$

shows $cdcl_{NOT}\text{-restart}^{**} \ S \ T \vee (no\text{-step } cdcl_W\text{-merge } T \wedge conflicting \ T \neq C\text{-True})$

proof –

consider

(fw) $cdcl_W\text{-merge } S \ T$

| (fw-r) $restart \ S \ T$

using $cdcl_W$ **by** (meson $cdcl_W\text{-merge-restart.simps } cdcl_W\text{-rf.cases fw-conflict fw-decide fw-forget}$
 $fw\text{-propagate}$)

then show ?thesis

proof cases

case fw

then have IH: $cdcl_{NOT}\text{-merged-bj-learn } S \ T \vee (no\text{-step } cdcl_W\text{-merge } T \wedge conflicting \ T \neq C\text{-True})$

using inv $cdcl_W\text{-merge-is-cdcl}_{NOT}\text{-merged-bj-learn}$ **by** blast

have $invS: inv_{NOT} \ S$

```

    using inv unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def by auto
  have ff2: cdclNOT++ S T  $\longrightarrow$  cdclNOT** S T
    by (meson tranclp-into-rtranclp)
  have ff3: no-dup ((convert-trail-from-W  $\circ$  trail) S)
    using invS by simp
  have cdclNOT  $\leq$  cdclNOT-restart
    by (auto simp: restart-ops.cdclNOT-raw-restart.simps)
  then show ?thesis
    using ff3 ff2 IH cdclNOT-merged-bj-learn-is-tranclp-cdclNOT
      rtranclp-mono[of cdclNOT cdclNOT-restart] invS predicate2D by blast
next
  case fw-r
  then show ?thesis by (blast intro: restart-ops.cdclNOT-raw-restart.intros)
qed
qed

```

abbreviation $\mu_{FW} :: 'st \Rightarrow nat$ **where**

$\mu_{FW} S \equiv$ (if no-step cdcl_W-merge S then 0 else $1 + \mu_{CDCL}$ -merged (set-mset (init-clss S)) S)

lemma cdcl_W-merge- μ_{FW} -decreasing:

```

  assumes
    inv: cdclW-all-struct-inv S and
    fw: cdclW-merge S T
  shows  $\mu_{FW} T < \mu_{FW} S$ 
proof -
  let ?A = init-clss S
  have atm-clauses: atms-of-msu (clauses S)  $\subseteq$  atms-of-msu ?A
    using inv unfolding cdclW-all-struct-inv-def no-strange-atm-def clauses-def by auto
  have atm-trail: atm-of ' lits-of (trail S)  $\subseteq$  atms-of-msu ?A
    using inv unfolding cdclW-all-struct-inv-def no-strange-atm-def clauses-def by auto
  have n-d: no-dup (trail S)
    using inv unfolding cdclW-all-struct-inv-def by (auto simp: cdclW-M-level-inv-decomp)
  have [simp]:  $\neg$  no-step cdclW-merge S
    using fw by auto
  have [simp]: init-clss S = init-clss T
    using cdclW-merge-restart-cdclW[of S T] inv rtranclp-cdclW-init-clss
      unfolding cdclW-all-struct-inv-def
      by (meson cdclW-merge.simps cdclW-merge-restart.simps cdclW-rf.simps fw)
  consider
    (merged) cdclNOT-merged-bj-learn S T
  | (n-s) no-step cdclW-merge T
  using cdclW-merge-is-cdclNOT-merged-bj-learn inv fw by blast
  then show ?thesis
  proof cases
  case merged
  then show ?thesis
    using cdclNOT-decreasing-measure'[OF - - atm-clauses] atm-trail n-d
    by (auto split: split-if)
next
  case n-s
  then show ?thesis by simp
qed
qed

```

lemma wf-cdcl_W-merge: wf {(T, S). cdcl_W-all-struct-inv S \wedge cdcl_W-merge S T}

apply (rule *wfP-if-measure*[of - - μ_{FW}])
using *cdcl_W-merge- μ_{FW} -decreasing* **by** *blast*

lemma *cdcl_W-all-struct-inv-tranclp-cdcl_W-merge-tranclp-cdcl_W-merge-cdcl_W-all-struct-inv*:

assumes

inv: *cdcl_W-all-struct-inv* *b*

cdcl_W-merge⁺⁺ *b a*

shows $(\lambda S T. \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge } S T)^{++} b a$

using *assms*(2)

proof *induction*

case *base*

then show ?*case* **using** *inv* **by** *auto*

next

case (step *c d*) **note** *st* = *this*(1) **and** *fw* = *this*(2) **and** *IH* = *this*(3)

have *cdcl_W-all-struct-inv* *c*

using *tranclp-into-rtranclp*[*OF st*] *cdcl_W-merge-rtranclp-cdcl_W*

assms(1) *rtranclp-cdcl_W-all-struct-inv-inv* *rtranclp-mono*[of *cdcl_W-merge* *cdcl_W***] **by** *fastforce*

then have $(\lambda S T. \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge } S T)^{++} c d$

using *fw* **by** *auto*

then show ?*case* **using** *IH* **by** *auto*

qed

lemma *wf-tranclp-cdcl_W-merge*: *wf* $\{(T, S). \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge}^{++} S T\}$

using *wf-trancl*[*OF wf-cdcl_W-merge*]

apply (rule *wf-subset*)

by (auto *simp*: *trancl-set-tranclp*

cdcl_W-all-struct-inv-tranclp-cdcl_W-merge-tranclp-cdcl_W-merge-cdcl_W-all-struct-inv)

lemma *backtrack-is-full1-cdcl_W-bj*:

assumes *bt*: *backtrack* *S T* **and** *inv*: *cdcl_W-M-level-inv* *S*

shows *full1* *cdcl_W-bj* *S T*

proof –

have *no-step* *cdcl_W-bj* *T*

using *bt inv backtrack-no-cdcl_W-bj* **by** *blast*

moreover have *cdcl_W-bj*⁺⁺ *S T*

using *bt* **by** *auto*

ultimately show ?*thesis* **unfolding** *full1-def* **by** *blast*

qed

lemma *rtrancl-cdcl_W-conflicting-true-cdcl_W-merge-restart*:

assumes *cdcl_W*** *S V* **and** *inv*: *cdcl_W-M-level-inv* *S* **and** *conflicting* *S* = *C-True*

shows (*cdcl_W-merge-restart*** *S V* \wedge *conflicting* *V* = *C-True*)

$\vee (\exists T U. \text{cdcl}_W\text{-merge-restart** } S T \wedge \text{conflicting } V \neq C\text{-True} \wedge \text{conflict } T U \wedge \text{cdcl}_W\text{-bj** } U V)$

using *assms*

proof *induction*

case *base*

then show ?*case* **by** *simp*

next

case (step *U V*) **note** *st* = *this*(1) **and** *cdcl_W* = *this*(2) **and** *IH* = *this*(3)[*OF this*(4–)] **and**

confl[*simp*] = *this*(5) **and** *inv* = *this*(4)

from *cdcl_W*

show ?*case*

proof (*cases*)

case *propagate*

moreover then have *conflicting* *U* = *C-True*

```

    by auto
  moreover have conflicting V = C-True
    using propagate by auto
  ultimately show ?thesis using IH cdclW-merge-restart.fw-r-propagate[of U V] by auto
next
case conflict
  moreover then have conflicting U = C-True
    by auto
  moreover have conflicting V ≠ C-True
    using conflict by auto
  ultimately show ?thesis using IH by auto
next
case other
  then show ?thesis
  proof cases
    case decide
      moreover then have conflicting U = C-True
        by auto
      ultimately show ?thesis using IH cdclW-merge-restart.fw-r-decide[of U V] by auto
  next
  case bj
    moreover {
      assume skip-or-resolve U V
      have f1: cdclW-bj++ U V
        by (simp add: local.bj tranclp.r-into-trancl)
      obtain T T' :: 'st where
        f2: cdclW-merge-restart** S U
          ∨ cdclW-merge-restart** S T ∧ conflicting U ≠ C-True
          ∧ conflict T T' ∧ cdclW-bj** T' U
        using IH confl by blast
      then have ?thesis
        proof -
          have conflicting V ≠ C-True ∧ conflicting U ≠ C-True
            using ⟨skip-or-resolve U V⟩ by auto
          then show ?thesis
            by (metis (no-types) IH f1 rtranclp-trans tranclp-into-rtranclp)
        qed
    }
  moreover {
    assume backtrack U V
    then have conflicting U ≠ C-True by auto
    then obtain T T' where
      cdclW-merge-restart** S T and
      conflicting U ≠ C-True and
      conflict T T' and
      cdclW-bj** T' U
      using IH confl by blast
    have invU: cdclW-M-level-inv U
      using inv rtranclp-cdclW-consistent-inv step.hyps(1) by blast
    then have conflicting V = C-True
      using ⟨backtrack U V⟩ inv by (auto elim: backtrack-levE
        simp: cdclW-M-level-inv-decomp)
    have full cdclW-bj T' V
      apply (rule rtranclp-fullI[of cdclW-bj T' U V])
      using ⟨cdclW-bj** T' U⟩ apply fast
  }

```

```

    using ⟨backtrack U V⟩ backtrack-is-full1-cdclW-bj invU unfolding full1-def full-def
    by blast
  then have ?thesis
    using cdclW-merge-restart.fw-r-conflict[of T T' V] ⟨conflict T T'⟩
    ⟨cdclW-merge-restart** S T⟩ ⟨conflicting V = C-True⟩ by auto
  }
  ultimately show ?thesis by (auto simp: cdclW-bj.simps)
qed
next
case rf
moreover then have conflicting U = C-True and conflicting V = C-True
  by (auto simp: cdclW-rf.simps)
ultimately show ?thesis using IH cdclW-merge-restart.fw-r-rf[of U V] by auto
qed
qed

```

lemma *no-step-cdcl_W-no-step-cdcl_W-merge-restart: no-step cdcl_W S \implies no-step cdcl_W-merge-restart S*
 by (auto simp: cdcl_W.simps cdcl_W-merge-restart.simps cdcl_W-o.simps cdcl_W-bj.simps)

lemma *no-step-cdcl_W-merge-restart-no-step-cdcl_W:*

```

assumes
  conflicting S = C-True and
  cdclW-M-level-inv S and
  no-step cdclW-merge-restart S
shows no-step cdclW S
proof -
{ fix S'
  assume conflict S S'
  then have cdclW S S' using cdclW.conflict by auto
  then have cdclW-M-level-inv S'
    using assms(2) cdclW-consistent-inv by blast
  then obtain S'' where full cdclW-bj S' S''
    using cdclW-bj-exists-normal-form[of S'] by auto
  then have False
    using ⟨conflict S S'⟩ assms(3) fw-r-conflict by blast
}
then show ?thesis
  using assms unfolding cdclW.simps cdclW-merge-restart.simps cdclW-o.simps cdclW-bj.simps
  by fastforce
qed

```

lemma *rtrancp-cdcl_W-merge-restart-no-step-cdcl_W-bj:*

```

assumes
  cdclW-merge-restart** S T and
  conflicting S = C-True
shows no-step cdclW-bj T
using assms
by (induction rule: rtrancp-induct)
(fastforce simp: cdclW-bj.simps cdclW-rf.simps cdclW-merge-restart.simps full-def)+

```

If *conflicting S \neq C-True*, we cannot say anything.

Remark that this theorem does not say anything about well-foundedness: even if you know that one relation is well-founded, it only states that the normal forms are shared.

lemma *conflicting-true-full-cdcl_W-iff-full-cdcl_W-merge:*

assumes *conf*: *conflicting* $S = C\text{-True}$ **and** *lev*: *cdcl_W-M-level-inv* S
shows *full cdcl_W* $S V \longleftrightarrow$ *full cdcl_W-merge-restart* $S V$
proof
assume *full*: *full cdcl_W-merge-restart* $S V$
then have *st*: *cdcl_W*** $S V$
using *rtranclp-mono*[*of cdcl_W-merge-restart cdcl_W***] *cdcl_W-merge-restart-cdcl_W*
unfolding *full-def* **by** *auto*

have *n-s*: *no-step cdcl_W-merge-restart* V
using *full unfolding full-def* **by** *auto*
have *n-s-bj*: *no-step cdcl_W-bj* V
using *rtranclp-cdcl_W-merge-restart-no-step-cdcl_W-bj confl full unfolding full-def* **by** *auto*
have $\bigwedge S'. \text{conflict } V S' \implies \text{cdcl}_W\text{-M-level-inv } S'$
using *cdcl_W.conflict cdcl_W-consistent-inv lev rtranclp-cdcl_W-consistent-inv st* **by** *blast*
then have $\bigwedge S'. \text{conflict } V S' \implies \text{False}$
using *n-s n-s-bj cdcl_W-bj-exists-normal-form cdcl_W-merge-restart.simps* **by** *meson*
then have *n-s-cdcl_W*: *no-step cdcl_W* V
using *n-s n-s-bj* **by** (*auto simp: cdcl_W.simps cdcl_W-o.simps cdcl_W-merge-restart.simps*)
then show *full cdcl_W* $S V$ **using** *st unfolding full-def* **by** *auto*
next
assume *full*: *full cdcl_W* $S V$
have *no-step cdcl_W-merge-restart* V
using *full no-step-cdcl_W-no-step-cdcl_W-merge-restart unfolding full-def* **by** *blast*
moreover
consider
 (*fw*) *cdcl_W-merge-restart*** $S V$ **and** *conflicting* $V = C\text{-True}$
 | (*bj*) $T U$ **where**
 *cdcl_W-merge-restart*** $S T$ **and**
 conflicting $V \neq C\text{-True}$ **and**
 conflict $T U$ **and**
 *cdcl_W-bj*** $U V$
using *full rtrancl-cdcl_W-conflicting-true-cdcl_W-merge-restart confl lev unfolding full-def*
by *meson*
then have *cdcl_W-merge-restart*** $S V$
proof *cases*
 case *fw*
 then show *?thesis* **by** *fast*
 next
 case (*bj* $T U$)
 have *no-step cdcl_W-bj* V
 by (*meson cdcl_W-o.bj full full-def other*)
 then have *full cdcl_W-bj* $U V$
 using $\langle \text{cdcl}_W\text{-bj** } U V \rangle$ **unfolding** *full-def* **by** *auto*
 then have *cdcl_W-merge-restart* $T V$
 using $\langle \text{conflict } T U \rangle$ *cdcl_W-merge-restart.fw-r-conflict* **by** *blast*
 then show *?thesis* **using** $\langle \text{cdcl}_W\text{-merge-restart** } S T \rangle$ **by** *auto*
 qed
ultimately show *full cdcl_W-merge-restart* $S V$ **unfolding** *full-def* **by** *fast*
qed

lemma *init-state-true-full-cdcl_W-iff-full-cdcl_W-merge*:
shows *full cdcl_W* (*init-state* N) $V \longleftrightarrow$ *full cdcl_W-merge-restart* (*init-state* N) V
by (*rule conflicting-true-full-cdcl_W-iff-full-cdcl_W-merge*) *auto*

19.4 FW with strategy

19.4.1 The intermediate step

inductive $cdcl_W-s' :: 'st \Rightarrow 'st \Rightarrow bool$ **where**

$conflict': full1\ cdcl_W-cp\ S\ S' \Longrightarrow cdcl_W-s'\ S\ S' \mid$

$decide': decide\ S\ S' \Longrightarrow no-step\ cdcl_W-cp\ S \Longrightarrow full\ cdcl_W-cp\ S'\ S'' \Longrightarrow cdcl_W-s'\ S\ S'' \mid$

$bj': full1\ cdcl_W-bj\ S\ S' \Longrightarrow no-step\ cdcl_W-cp\ S \Longrightarrow full\ cdcl_W-cp\ S'\ S'' \Longrightarrow cdcl_W-s'\ S\ S''$

inductive-cases $cdcl_W-s'E: cdcl_W-s'\ S\ T$

lemma $rtrancp-cdcl_W-bj-full1-cdclp-cdcl_W-stgy:$

$cdcl_W-bj^{**}\ S\ S' \Longrightarrow full\ cdcl_W-cp\ S'\ S'' \Longrightarrow cdcl_W-stgy^{**}\ S\ S''$

proof (induction rule: converse-rtrancp-induct)

case *base*

then show $?case$ **by** (metis $cdcl_W-stgy.conflict'$ $full-unfold\ rtrancp.simps$)

next

case (step $T\ U$) **note** $st = this(2)$ **and** $bj = this(1)$ **and** $IH = this(3)[OF\ this(4)]$

have $no-step\ cdcl_W-cp\ T$

using bj **by** (auto simp add: $cdcl_W-bj.simps$)

consider

(U) $U = S'$

| (U') U' **where** $cdcl_W-bj\ U\ U'$ **and** $cdcl_W-bj^{**}\ U'\ S'$

using st **by** (metis converse-rtrancpE)

then show $?case$

proof *cases*

case U

then show $?thesis$

using ($no-step\ cdcl_W-cp\ T$) $cdcl_W-o.bj\ local.bj\ other'$ *step.prem*s **by** (meson $r-into-rtrancp$)

next

case U' **note** $U' = this(1)$

have $no-step\ cdcl_W-cp\ U$

using U' **by** (fastforce simp: $cdcl_W-cp.simps\ cdcl_W-bj.simps$)

then have $full\ cdcl_W-cp\ U\ U$

by (simp add: $full-unfold$)

then have $cdcl_W-stgy\ T\ U$

using ($no-step\ cdcl_W-cp\ T$) $cdcl_W-stgy.simps\ local.bj\ cdcl_W-o.bj$ **by** meson

then show $?thesis$ **using** IH **by** auto

qed

qed

lemma $cdcl_W-s'-is-rtrancp-cdcl_W-stgy:$

$cdcl_W-s'\ S\ T \Longrightarrow cdcl_W-stgy^{**}\ S\ T$

apply (induction rule: $cdcl_W-s'.induct$)

apply (auto intro: $cdcl_W-stgy.intros$)[]

apply (meson decide other' $r-into-rtrancp$)

by (metis $full1-def\ rtrancp-cdcl_W-bj-full1-cdclp-cdcl_W-stgy\ rtrancp-into-rtrancp$)

lemma $cdcl_W-cp-cdcl_W-bj-bissimulation:$

assumes

$full\ cdcl_W-cp\ T\ U$ **and**

$cdcl_W-bj^{**}\ T\ T'$ **and**

$cdcl_W-all-struct-inv\ T$ **and**

$no-step\ cdcl_W-bj\ T'$

shows $full\ cdcl_W-cp\ T'\ U$

$\vee (\exists\ U'\ U''. full\ cdcl_W-cp\ T'\ U'' \wedge full1\ cdcl_W-bj\ U\ U' \wedge full\ cdcl_W-cp\ U'\ U'' \wedge cdcl_W-s'^{**}\ U\ U'')$

```

using assms(2,1,3,4)
proof (induction rule: rtrancp-induct)
  case base
  then show ?case by blast
next
  case (step  $T' T''$ ) note  $st = this(1)$  and  $bj = this(2)$  and  $IH = this(3)[OF\ this(4,5)]$  and
     $full = this(4)$  and  $inv = this(5)$ 
  have  $cdcl_W^{**} T T''$ 
    by (metis (no-types, lifting)  $cdcl_W$ -o.bj local.bj mono-rtrancp[of  $cdcl_W$ -bj  $cdcl_W T T''$ ] other
       $st\ rtrancp.rtrancp$ -into- $rtrancp$ )
  then have  $inv$ - $T''$ :  $cdcl_W$ -all-struct- $inv T''$ 
    using  $inv\ rtrancp$ - $cdcl_W$ -all-struct- $inv$ - $inv$  by blast
  have  $cdcl_W$ -bj++  $T T''$ 
    using local.bj  $st$  by auto
  have  $full1\ cdcl_W$ -bj  $T T''$ 
    by (metis  $\langle cdcl_W$ -bj++  $T T'' \rangle$  full1-def step.prems(3))
  then have  $T = U$ 
  proof –
    obtain  $Z$  where  $cdcl_W$ -bj  $T Z$ 
      by (meson trancpD  $\langle cdcl_W$ -bj++  $T T'' \rangle$ )
    { assume  $cdcl_W$ -cp++  $T U$ 
      then obtain  $Z'$  where  $cdcl_W$ -cp  $T Z'$ 
        by (meson trancpD)
      then have False
        using  $\langle cdcl_W$ -bj  $T Z \rangle$  by (fastforce simp:  $cdcl_W$ -bj.simss  $cdcl_W$ -cp.simss)
      }
    then show ?thesis
      using full unfolding full-def rtrancp-unfold by blast
  qed
obtain  $U''$  where  $full\ cdcl_W$ -cp  $T'' U''$ 
  using  $cdcl_W$ -cp-normalized-element-all- $inv\ inv$ - $T''$  by blast
moreover then have  $cdcl_W$ -stgy**  $U U''$ 
  by (metis  $\langle T = U \rangle$   $\langle cdcl_W$ -bj++  $T T'' \rangle$  rtrancp- $cdcl_W$ -bj-full1- $cdclp$ - $cdcl_W$ -stgy rtrancp-unfold)
moreover have  $cdcl_W$ -s**  $U U''$ 
  proof –
    obtain  $ss :: 'st \Rightarrow 'st$  where
       $f1: \forall x2. (\exists v3. cdcl_W$ -cp  $x2\ v3) = cdcl_W$ -cp  $x2\ (ss\ x2)$ 
      by moura
    have  $\neg cdcl_W$ -cp  $U\ (ss\ U)$ 
      by (meson full full-def)
    then show ?thesis
      using  $f1$  by (metis (no-types)  $\langle T = U \rangle$   $\langle full1\ cdcl_W$ -bj  $T T'' \rangle$  bj' calculation(1)
        r-into-rtrancp)
  qed
ultimately show ?case
  using  $\langle full1\ cdcl_W$ -bj  $T T'' \rangle$   $\langle full\ cdcl_W$ -cp  $T'' U'' \rangle$  unfolding  $\langle T = U \rangle$  by blast
qed

```

lemma $cdcl_W$ -cp- $cdcl_W$ -bj-bissimulation':

```

assumes
  full  $cdcl_W$ -cp  $T U$  and
   $cdcl_W$ -bj**  $T T'$  and
   $cdcl_W$ -all-struct- $inv T$  and
  no-step  $cdcl_W$ -bj  $T'$ 
shows full  $cdcl_W$ -cp  $T' U$ 

```

```


$$\vee (\exists U'. \text{full1 } \text{cdcl}_W\text{-bj } U \ U' \wedge (\forall U''. \text{full } \text{cdcl}_W\text{-cp } U' \ U'' \longrightarrow \text{full } \text{cdcl}_W\text{-cp } T' \ U''$$


$$\wedge \text{cdcl}_W\text{-s}^{***} \ U \ U''))$$

using assms(2,1,3,4)
proof (induction rule: rtrancp-induct)
  case base
  then show ?case by blast
next
  case (step  $T' \ T''$ ) note  $st = \text{this}(1)$  and  $bj = \text{this}(2)$  and  $IH = \text{this}(3)[OF \ \text{this}(4,5)]$  and
     $\text{full} = \text{this}(4)$  and  $\text{inv} = \text{this}(5)$ 
  have  $\text{cdcl}_W^{**} \ T \ T''$ 
    by (metis (no-types, lifting)  $\text{cdcl}_W\text{-o.bj local.bj mono-rtrancp}[of \ \text{cdcl}_W\text{-bj } \text{cdcl}_W \ T \ T'']$  other st
      rtrancp.rtrancp-into-rtrancp)
  then have  $\text{inv-}T''$ :  $\text{cdcl}_W\text{-all-struct-inv } T''$ 
    using  $\text{inv rtrancp-cdcl}_W\text{-all-struct-inv-inv}$  by blast
  have  $\text{cdcl}_W\text{-bj}^{++} \ T \ T''$ 
    using local.bj st by auto
  have  $\text{full1 } \text{cdcl}_W\text{-bj } T \ T''$ 
    by (metis  $\langle \text{cdcl}_W\text{-bj}^{++} \ T \ T'' \rangle$  full1-def step.prems(3))
  then have  $T = U$ 
  proof –
    obtain  $Z$  where  $\text{cdcl}_W\text{-bj } T \ Z$ 
      by (meson trancpD  $\langle \text{cdcl}_W\text{-bj}^{++} \ T \ T'' \rangle$ )
    { assume  $\text{cdcl}_W\text{-cp}^{++} \ T \ U$ 
      then obtain  $Z'$  where  $\text{cdcl}_W\text{-cp } T \ Z'$ 
        by (meson trancpD)
      then have False
        using  $\langle \text{cdcl}_W\text{-bj } T \ Z \rangle$  by (fastforce simp: cdcl}_W\text{-bj.simps cdcl}_W\text{-cp.simps)
      }
    then show ?thesis
      using full unfolding full-def rtrancp-unfold by blast
  qed
{ fix  $U''$ 
  assume  $\text{full } \text{cdcl}_W\text{-cp } T'' \ U''$ 
  moreover then have  $\text{cdcl}_W\text{-stgy}^{**} \ U \ U''$ 
    by (metis  $\langle T = U \rangle \langle \text{cdcl}_W\text{-bj}^{++} \ T \ T'' \rangle$  rtrancp-cdcl}_W\text{-bj-full1-cdclp-cdcl}_W\text{-stgy rtrancp-unfold)
  moreover have  $\text{cdcl}_W\text{-s}^{***} \ U \ U''$ 
  proof –
    obtain  $ss :: 'st \Rightarrow 'st$  where
       $f1: \forall x2. (\exists v3. \text{cdcl}_W\text{-cp } x2 \ v3) = \text{cdcl}_W\text{-cp } x2 \ (ss \ x2)$ 
      by moura
    have  $\neg \text{cdcl}_W\text{-cp } U \ (ss \ U)$ 
      by (meson assms(1) full-def)
    then show ?thesis
      using  $f1$  by (metis (no-types)  $\langle T = U \rangle \langle \text{full1 } \text{cdcl}_W\text{-bj } T \ T'' \rangle$  bj' calculation(1)
        r-into-rtrancp)
    qed
  ultimately have  $\text{full1 } \text{cdcl}_W\text{-bj } U \ T''$  and  $\text{cdcl}_W\text{-s}^{***} \ T'' \ U''$ 
    using  $\langle \text{full1 } \text{cdcl}_W\text{-bj } T \ T'' \rangle \langle \text{full } \text{cdcl}_W\text{-cp } T'' \ U'' \rangle$  unfolding  $\langle T = U \rangle$ 
    apply blast
    by (metis  $\langle \text{full } \text{cdcl}_W\text{-cp } T'' \ U'' \rangle \text{cdcl}_W\text{-s'.simps full-unfold rtrancp.simps}$ )
  }
then show ?case
  using  $\langle \text{full1 } \text{cdcl}_W\text{-bj } T \ T'' \rangle$  full bj' unfolding  $\langle T = U \rangle$  full-def by (metis r-into-rtrancp)
qed

```

```

lemma cdclW-stgy-cdclW-s'-connected:
  assumes cdclW-stgy S U and cdclW-all-struct-inv S
  shows cdclW-s' S U
     $\vee (\exists U'. \text{full1 } \text{cdcl}_W\text{-bj } U \ U' \wedge (\forall U''. \text{full } \text{cdcl}_W\text{-cp } U' \ U'' \longrightarrow \text{cdcl}_W\text{-s' } S \ U''))$ 
  using assms
proof (induction rule: cdclW-stgy.induct)
  case (conflict' T)
  then have cdclW-s' S T
    using cdclW-s'.conflict' by blast
  then show ?case
    by blast
next
case (other' T U) note o = this(1) and n-s = this(2) and full = this(3) and inv = this(4)
show ?case
  using o
proof cases
  case decide
  then show ?thesis using cdclW-s'.simps full n-s by blast
next
case bj
have inv-T: cdclW-all-struct-inv T
  using cdclW-all-struct-inv-inv o other other'.prems by blast
consider
  (cp) full cdclW-cp T U and no-step cdclW-bj T
  | (fbj) T' where full1 cdclW-bj T T'
apply (cases no-step cdclW-bj T)
  using full apply blast
  using cdclW-bj-exists-normal-form[of T] inv-T unfolding cdclW-all-struct-inv-def
  by (metis full-unfold)
then show ?thesis
proof cases
  case cp
  then show ?thesis
  proof –
  obtain ss :: 'st  $\Rightarrow$  'st where
    f1:  $\forall s \ sa \ sb. (\neg \text{full1 } \text{cdcl}_W\text{-bj } s \ sa \vee \text{cdcl}_W\text{-cp } s \ (ss \ s) \vee \neg \text{full } \text{cdcl}_W\text{-cp } sa \ sb)$ 
     $\vee \text{cdcl}_W\text{-s' } s \ sb$ 
  using bj' by moura
  have full1 cdclW-bj S T
  by (simp add: cp(2) full1-def local.bj tranclp.r-into-trancl)
  then show ?thesis
  using f1 full n-s by blast
  qed
next
case (fbj U')
then have full1 cdclW-bj S U'
  using bj unfolding full1-def by auto
moreover have no-step cdclW-cp S
  using n-s by blast
moreover have T = U
  using full fbj unfolding full1-def full-def rtranclp-unfold
  by (force dest!: tranclpD simp:cdclW-bj.simps)
  ultimately show ?thesis using cdclW-s'.bj'[of S U] using fbj by blast
qed
qed

```

qed

lemma *cdcl_W-stgy-cdcl_W-s'-connected'*:
assumes *cdcl_W-stgy S U* **and** *cdcl_W-all-struct-inv S*
shows *cdcl_W-s' S U*
 $\vee (\exists U' U''. \text{cdcl}_W\text{-s'} S U'' \wedge \text{full1 } \text{cdcl}_W\text{-bj } U U' \wedge \text{full } \text{cdcl}_W\text{-cp } U' U'')$
using *assms*
proof (*induction rule: cdcl_W-stgy.induct*)
case (*conflict' T*)
then have *cdcl_W-s' S T*
using *cdcl_W-s'.conflict'* **by** *blast*
then show *?case*
by *blast*
next
case (*other' T U*) **note** *o = this(1)* **and** *n-s = this(2)* **and** *full = this(3)* **and** *inv = this(4)*
show *?case*
using *o*
proof *cases*
case *decide*
then show *?thesis* **using** *cdcl_W-s'.simps full n-s* **by** *blast*
next
case *bj*
have *cdcl_W-all-struct-inv T*
using *cdcl_W-all-struct-inv-inv o other other'.prems* **by** *blast*
then obtain *T' where T': full cdcl_W-bj T T'*
using *cdcl_W-bj-exists-normal-form unfolding full-def cdcl_W-all-struct-inv-def* **by** *metis*
then have *full cdcl_W-bj S T'*
proof –
have *f1: cdcl_W-bj** T T' \wedge no-step cdcl_W-bj T'*
by (*metis (no-types) T' full-def*)
then have *cdcl_W-bj** S T'*
by (*meson converse-rtranclp-into-rtranclp local.bj*)
then show *?thesis*
using *f1* **by** (*simp add: full-def*)
qed
have *cdcl_W-bj** T T'*
using *T' unfolding full-def* **by** *simp*
have *cdcl_W-all-struct-inv T*
using *cdcl_W-all-struct-inv-inv o other other'.prems* **by** *blast*
then consider
 $(T'U) \text{ full } \text{cdcl}_W\text{-cp } T' U$
 $| (U) U' U'' \text{ where}$
 $\text{full } \text{cdcl}_W\text{-cp } T' U'' \text{ and}$
 $\text{full1 } \text{cdcl}_W\text{-bj } U U' \text{ and}$
 $\text{full } \text{cdcl}_W\text{-cp } U' U'' \text{ and}$
 $\text{cdcl}_W\text{-s}^{l**} U U''$
using *cdcl_W-cp-cdcl_W-bj-bissimulation[OF full $\langle \text{cdcl}_W\text{-bj** } T T' \rangle$ T' unfolding full-def*
by *blast*
then show *?thesis* **by** (*metis T' cdcl_W-s'.simps full-fullI local.bj n-s*)
qed
qed

lemma *cdcl_W-stgy-cdcl_W-s'-no-step*:
assumes *cdcl_W-stgy S U* **and** *cdcl_W-all-struct-inv S* **and** *no-step cdcl_W-bj U*
shows *cdcl_W-s' S U*

```

using cdclW-stgy-cdclW-s'-connected[OF assms(1,2)] assms(3)
by (metis (no-types, lifting) full1-def trancplD)

lemma rtrancpl-cdclW-stgy-connected-to-rtrancpl-cdclW-s':
  assumes cdclW-stgy** S U and inv: cdclW-M-level-inv S
  shows cdclW-s'** S U  $\vee$  ( $\exists T. \text{cdcl}_W\text{-s}'^{**} S T \wedge \text{cdcl}_W\text{-bj}^{++} T U \wedge \text{conflicting } U \neq C\text{-True}$ )
  using assms(1)
proof induction
  case base
  then show ?case by simp
next
  case (step T V) note st = this(1) and o = this(2) and IH = this(3)
  from o show ?case
  proof cases
    case conflict'
    then have f2: cdclW-s' T V
    using cdclW-s'.conflict' by blast
    obtain ss :: 'st where
      f3: S = T  $\vee$  cdclW-stgy** S ss  $\wedge$  cdclW-stgy ss T
      by (metis (full-types) rtrancpl.simps st)
    obtain ssa :: 'st where
      cdclW-cp T ssa
    using conflict' by (metis (no-types) full1-def trancplD)
    then have S = T
    using f3 by (metis (no-types) cdclW-stgy.simps full-def full1-def)
    then show ?thesis
    using f2 by blast
  next
  case (other' U) note o = this(1) and n-s = this(2) and full = this(3)
  then show ?thesis
  using o
  proof (cases rule: cdclW-o-rule-cases)
    case decide
    then have cdclW-s'** S T
    using IH by auto
    then show ?thesis
    by (meson decide decide' full n-s rtrancpl.rtrancl-into-rtrancl)
  next
  case backtrack
  consider
    (s') cdclW-s'** S T
    | (bj) S' where cdclW-s'** S S' and cdclW-bj++ S' T and conflicting T  $\neq$  C-True
    using IH by blast
  then show ?thesis
  proof cases
    case s'
    moreover
    have cdclW-M-level-inv T
    using inv local.step(1) rtrancpl-cdclW-stgy-consistent-inv by auto
    then have full1 cdclW-bj T U
    using backtrack-is-full1-cdclW-bj backtrack by blast
    then have cdclW-s' T V
    using full bj' n-s by blast
    ultimately show ?thesis by auto
  next

```

```

    case (bj S') note S-S' = this(1) and bj-T = this(2)
    have no-step cdclW-cp S'
      using bj-T by (fastforce simp: cdclW-cp.simps cdclW-bj.simps dest!: tranclpD)
    moreover
      have cdclW-M-level-inv T
        using inv local.step(1) rtranclp-cdclW-stgy-consistent-inv by auto
      then have full1 cdclW-bj T U
        using backtrack-is-full1-cdclW-bj backtrack by blast
      then have full1 cdclW-bj S' U
        using bj-T unfolding full1-def by fastforce
      ultimately have cdclW-s' S' V using full by (simp add: bj')
      then show ?thesis using S-S' by auto
    qed
  next
    case skip
    then have [simp]: U = V
      using full converse-rtranclpE unfolding full-def by fastforce

    consider
      (s') cdclW-s'** S T
    | (bj) S' where cdclW-s'** S S' and cdclW-bj++ S' T and conflicting T ≠ C-True
    using IH by blast
  then show ?thesis
  proof cases
    case s'
    have cdclW-bj++ T V
      using skip by force
    moreover have conflicting V ≠ C-True
      using skip by auto
    ultimately show ?thesis using s' by auto
  next
    case (bj S') note S-S' = this(1) and bj-T = this(2)
    have cdclW-bj++ S' V
      using skip bj-T by (metis ⟨U = V⟩ cdclW-bj.skip tranclp.simps)

    moreover have conflicting V ≠ C-True
      using skip by auto
    ultimately show ?thesis using S-S' by auto
  qed
next
  case resolve
  then have [simp]: U = V
    using full converse-rtranclpE unfolding full-def by fastforce
  consider
    (s') cdclW-s'** S T
  | (bj) S' where cdclW-s'** S S' and cdclW-bj++ S' T and conflicting T ≠ C-True
  using IH by blast
then show ?thesis
proof cases
  case s'
  have cdclW-bj++ T V
    using resolve by force
  moreover have conflicting V ≠ C-True
    using resolve by auto
  ultimately show ?thesis using s' by auto

```

```

    next
    case (bj S') note S-S' = this(1) and bj-T = this(2)
    have cdclW-bj++ S' V
      using resolve bj-T by (metis ⟨U = V⟩ cdclW-bj.resolve tranclp.simps)
    moreover have conflicting V ≠ C-True
      using resolve by auto
    ultimately show ?thesis using S-S' by auto
  qed
qed
qed
qed

lemma n-step-cdclW-stgy-iff-no-step-cdclW-cl-cdclW-o:
  assumes inv: cdclW-all-struct-inv S
  shows no-step cdclW-s' S ⟷ no-step cdclW-cp S ∧ no-step cdclW-o S (is ?S' S ⟷ ?C S ∧ ?O S)
proof
  assume ?C S ∧ ?O S
  then show ?S' S
    by (auto simp: cdclW-s'.simps full1-def tranclp-unfold-begin)
next
  assume n-s: ?S' S
  have ?C S
  proof (rule ccontr)
    assume ¬ ?thesis
    then obtain S' where cdclW-cp S S'
      by auto
    then obtain T where full1 cdclW-cp S T
      using cdclW-cp-normalized-element-all-inv inv by (metis (no-types, lifting) full-unfold)
    then show False using n-s cdclW-s'.conflict' by blast
  qed
  moreover have ?O S
  proof (rule ccontr)
    assume ¬ ?thesis
    then obtain S' where cdclW-o S S'
      by auto
    then obtain T where full1 cdclW-cp S' T
      using cdclW-cp-normalized-element-all-inv inv
    by (meson cdclW-all-struct-inv-def n-s
        cdclW-stgy-cdclW-s'-connected' cdclW-then-exists-cdclW-stgy-step )
    then show False using n-s by (meson ⟨cdclW-o S S'⟩ cdclW-all-struct-inv-def
        cdclW-stgy-cdclW-s'-connected' cdclW-then-exists-cdclW-stgy-step inv)
  qed
  ultimately show ?C S ∧ ?O S by auto
qed

lemma cdclW-s'-tranclp-cdclW:
  cdclW-s' S S' ⟹ cdclW++ S S'
proof (induct rule: cdclW-s'.induct)
  case conflict'
  then show ?case
    by (simp add: full1-def tranclp-cdclW-cp-tranclp-cdclW)
next
  case decide'
  then show ?case
    using cdclW-stgy.simps cdclW-stgy-tranclp-cdclW by (meson cdclW-o.simps)

```


next

case (bj' Sa S'a S'') **note** a2 = this(1) **and** a1 = this(2) **and** n-s = this(3)
obtain ss :: 'st ⇒ 'st ⇒ ('st ⇒ 'st ⇒ bool) ⇒ 'st **where**
 ∀ x0 x1 x2. (∃ v3. x2 x1 v3 ∧ x2** v3 x0) = (x2 x1 (ss x0 x1 x2) ∧ x2** (ss x0 x1 x2) x0)
by moura
then have f3: ∀ p s sa. ¬ p⁺⁺ s sa ∨ p s (ss sa s p) ∧ p** (ss sa s p) sa
by (metis (full-types) tranclpD)
have cdcl_W-bj⁺⁺ Sa S'a ∧ no-step cdcl_W-bj S'a
using a2 **by** (simp add: full1-def)
then have cdcl_W-bj Sa (ss S'a Sa cdcl_W-bj) ∧ cdcl_W-bj** (ss S'a Sa cdcl_W-bj) S'a
using f3 **by** auto
then show cdcl_W⁺⁺ Sa S''
using a1 n-s **by** (meson bj other rtranclp-cdcl_W-bj-full1-cdclp-cdcl_W-stgy
 rtranclp-cdcl_W-stgy-rtranclp-cdcl_W rtranclp-into-tranclp2)

qed

lemma tranclp-cdcl_W-s'-tranclp-cdcl_W:
 cdcl_W-s'⁺⁺ S S' ⇒ cdcl_W⁺⁺ S S'
apply (induct rule: tranclp.induct)
using cdcl_W-s'-tranclp-cdcl_W **apply** blast
by (meson cdcl_W-s'-tranclp-cdcl_W tranclp-trans)

lemma rtranclp-cdcl_W-s'-rtranclp-cdcl_W:
 cdcl_W-s'^{**} S S' ⇒ cdcl_W^{**} S S'
using rtranclp-unfold[of cdcl_W-s' S S'] tranclp-cdcl_W-s'-tranclp-cdcl_W[of S S'] **by** auto

lemma full-cdcl_W-stgy-iff-full-cdcl_W-s':
assumes inv: cdcl_W-all-struct-inv S
shows full cdcl_W-stgy S T ⇔ full cdcl_W-s' S T (**is** ?S ⇔ ?S')

proof

assume ?S'
then have cdcl_W^{**} S T
using rtranclp-cdcl_W-s'-rtranclp-cdcl_W[of S T] **unfolding** full-def **by** blast
then have inv': cdcl_W-all-struct-inv T
using rtranclp-cdcl_W-all-struct-inv-inv inv **by** blast
have cdcl_W-stgy^{**} S T
using ⟨?S'⟩ **unfolding** full-def
using cdcl_W-s'-is-rtranclp-cdcl_W-stgy rtranclp-mono[of cdcl_W-s' cdcl_W-stgy^{**}] **by** auto
then show ?S
using ⟨?S'⟩ inv' cdcl_W-stgy-cdcl_W-s'-connected' **unfolding** full-def **by** blast

next

assume ?S
then have inv-T:cdcl_W-all-struct-inv T
by (metis assms full-def rtranclp-cdcl_W-all-struct-inv-inv rtranclp-cdcl_W-stgy-rtranclp-cdcl_W)

consider

(s') cdcl_W-s'^{**} S T
 | (st) S' **where** cdcl_W-s'^{**} S S' **and** cdcl_W-bj⁺⁺ S' T **and** conflicting T ≠ C-True
using rtranclp-cdcl_W-stgy-connected-to-rtranclp-cdcl_W-s'[of S T] inv ⟨?S⟩
unfolding full-def cdcl_W-all-struct-inv-def
by blast

then show ?S'

proof cases

case s'

then show ?thesis

```

    by (metis ⟨full cdclW-stgy S T⟩ inv-T cdclW-all-struct-inv-def cdclW-s'.sims
        cdclW-stgy.conflict' cdclW-then-exists-cdclW-stgy-step full-def
        n-step-cdclW-stgy-iff-no-step-cdclW-cl-cdclW-o)
next
case (st S')
have full cdclW-cp T T
  using conflicting-clause-full-cdclW-cp st(3) by blast
moreover
  have n-s: no-step cdclW-bj T
    by (metis ⟨full cdclW-stgy S T⟩ bj inv-T cdclW-all-struct-inv-def
        cdclW-then-exists-cdclW-stgy-step full-def)
  then have full1 cdclW-bj S' T
    using st(2) unfolding full1-def by blast
moreover have no-step cdclW-cp S'
  using st(2) by (fastforce dest!: tranclpD simp: cdclW-cp.sims cdclW-bj.sims)
ultimately have cdclW-s' S' T
  using cdclW-s'.bj'[of S' T T] by blast
then have cdclW-sts* S T
  using st(1) by auto
moreover have no-step cdclW-s' T
  using inv-T by (metis ⟨full cdclW-cp T T⟩ ⟨full cdclW-stgy S T⟩ cdclW-all-struct-inv-def
        cdclW-then-exists-cdclW-stgy-step full-def n-step-cdclW-stgy-iff-no-step-cdclW-cl-cdclW-o)
ultimately show ?thesis
  unfolding full-def by blast
qed
qed

```

lemma *conflict-step-cdcl_W-stgy-step*:

```

assumes
  conflict S T
  cdclW-all-struct-inv S
shows ∃ T. cdclW-stgy S T
proof -
  obtain U where full cdclW-cp S U
    using cdclW-cp-normalized-element-all-inv assms by blast
  then have full1 cdclW-cp S U
    by (metis cdclW-cp.conflict' assms(1) full-unfold)
  then show ?thesis using cdclW-stgy.conflict' by blast
qed

```

lemma *decide-step-cdcl_W-stgy-step*:

```

assumes
  decide S T
  cdclW-all-struct-inv S
shows ∃ T. cdclW-stgy S T
proof -
  obtain U where full cdclW-cp T U
    using cdclW-cp-normalized-element-all-inv by (meson assms(1) assms(2) cdclW-all-struct-inv-inv
        cdclW-cp-normalized-element-all-inv decide other)
  then show ?thesis
    by (metis assms cdclW-cp-normalized-element-all-inv cdclW-stgy.conflict' decide full-unfold
        other')
qed

```

lemma *rtranclp-cdcl_W-cp-conflicting-C-Clause*:

$cdcl_W\text{-cp}^{**} S T \implies \text{conflicting } S = C\text{-Clause } D \implies S = T$
using *rtranclpD tranclpD by fastforce*

inductive *cdcl_W-merge-cp* :: '*st* \Rightarrow '*st* \Rightarrow bool **where**
conflict'[*intro*]: $\text{conflict } S T \implies \text{full } cdcl_W\text{-bj } T U \implies cdcl_W\text{-merge-cp } S U$ |
propagate'[*intro*]: $\text{propagate}^{++} S S' \implies cdcl_W\text{-merge-cp } S S'$

lemma *cdcl_W-merge-restart-cases*[*consumes 1, case-names conflict propagate*]:
assumes
cdcl_W-merge-cp S U and
 $\bigwedge T. \text{conflict } S T \implies \text{full } cdcl_W\text{-bj } T U \implies P$ **and**
 $\text{propagate}^{++} S U \implies P$
shows *P*
using *assms unfolding cdcl_W-merge-cp.simps by auto*

lemma *cdcl_W-merge-cp-tranclp-cdcl_W-merge*:
 $cdcl_W\text{-merge-cp } S T \implies cdcl_W\text{-merge}^{++} S T$
apply (*induction rule: cdcl_W-merge-cp.induct*)
using *cdcl_W-merge.simps apply auto[1]*
using *tranclp-mono[of propagate cdcl_W-merge] fw-propagate by blast*

lemma *rtranclp-cdcl_W-merge-cp-rtranclp-cdcl_W*:
 $cdcl_W\text{-merge-cp}^{**} S T \implies cdcl_W^{**} S T$
apply (*induction rule: rtranclp-induct*)
apply *simp*
unfolding *cdcl_W-merge-cp.simps by (meson cdcl_W-merge-restart-cdcl_W fw-r-conflict*
rtranclp-propagate-is-rtranclp-cdcl_W rtranclp-trans tranclp-into-rtranclp)

lemma *full1-cdcl_W-bj-no-step-cdcl_W-bj*:
 $\text{full1 } cdcl_W\text{-bj } S T \implies \text{no-step } cdcl_W\text{-cp } S$
by (*metis rtranclp-unfold cdcl_W-cp-conflicting-not-empty conflicting-clause.exhaust full1-def*
rtranclp-cdcl_W-merge-restart-no-step-cdcl_W-bj tranclpD)

inductive *cdcl_W-s'-without-decide* **where**
conflict'-without-decide[*intro*]: $\text{full1 } cdcl_W\text{-cp } S S' \implies cdcl_W\text{-s'-without-decide } S S'$ |
bj'-without-decide[*intro*]: $\text{full1 } cdcl_W\text{-bj } S S' \implies \text{no-step } cdcl_W\text{-cp } S \implies \text{full } cdcl_W\text{-cp } S' S''$
 $\implies cdcl_W\text{-s'-without-decide } S S''$

lemma *rtranclp-cdcl_W-s'-without-decide-rtranclp-cdcl_W*:
 $cdcl_W\text{-s'-without-decide}^{**} S T \implies cdcl_W^{**} S T$
apply (*induction rule: rtranclp-induct*)
apply *simp*
by (*meson cdcl_W-s'.simps cdcl_W-s'-tranclp-cdcl_W cdcl_W-s'-without-decide.simps*
rtranclp-tranclp-tranclp tranclp-into-rtranclp)

lemma *rtranclp-cdcl_W-s'-without-decide-rtranclp-cdcl_W-s'*:
 $cdcl_W\text{-s'-without-decide}^{**} S T \implies cdcl_W\text{-s}'^{**} S T$
proof (*induction rule: rtranclp-induct*)
case *base*
then show ?*case* **by** *simp*
next
case (*step y z*) **note** *a2 = this(2)* **and** *a1 = this(3)*
have $cdcl_W\text{-s}' y z$
using *a2 by (metis (no-types) bj' cdcl_W-s'.conflict' cdcl_W-s'-without-decide.cases)*
then show $cdcl_W\text{-s}'^{**} S z$

```

    using a1 by (meson r-into-rtrancpl rtrancpl-trans)
qed

lemma rtrancpl-cdclW-merge-cp-is-rtrancpl-cdclW-s'-without-decide:
  assumes
    cdclW-merge-cp** S V
    conflicting S = C-True
  shows
    (cdclW-s'-without-decide** S V)
    ∨ (∃ T. cdclW-s'-without-decide** S T ∧ propagate++ T V)
    ∨ (∃ T U. cdclW-s'-without-decide** S T ∧ full1 cdclW-bj T U ∧ propagate** U V)
  using assms
proof (induction rule: rtrancpl-induct)
  case base
  then show ?case by simp
next
  case (step U V) note st = this(1) and cp = this(2) and IH = this(3)[OF this(4)]
  from cp show ?case
  proof (cases rule: cdclW-merge-restart-cases)
    case propagate
    then show ?thesis using IH by (meson rtrancpl-trancpl-trancpl trancpl-into-rtrancpl)
  next
    case (conflict U') note confl = this(1) and bj = this(2)
    have full1-U-U': full1 cdclW-cp U U'
    by (simp add: conflict-is-full1-cdclW-cp local.conflict(1))
    consider
      (s') cdclW-s'-without-decide** S U
    | (propa) T' where cdclW-s'-without-decide** S T' and propagate++ T' U
    | (bj-prop) T' T'' where
      cdclW-s'-without-decide** S T' and
      full1 cdclW-bj T' T'' and
      propagate** T'' U
    using IH by blast
  then show ?thesis
  proof cases
    case s'
    have cdclW-s'-without-decide U U'
    using full1-U-U' conflict'-without-decide by blast
    then have cdclW-s'-without-decide** S U'
    using ⟨cdclW-s'-without-decide** S U⟩ by auto
    moreover have U' = V ∨ full1 cdclW-bj U' V
    using bj by (meson full-unfold)
    ultimately show ?thesis by blast
  next
    case propa note s' = this(1) and T'-U = this(2)
    have full1 cdclW-cp T' U'
    using rtrancpl-mono[of propagate cdclW-cp] T'-U cdclW-cp.propagate' full1-U-U'
    rtrancpl-full1I[of cdclW-cp T'] by (metis (full-types) predicate2D predicate2I
      trancpl-into-rtrancpl)
    have cdclW-s'-without-decide** S U'
    using ⟨full1 cdclW-cp T' U'⟩ conflict'-without-decide s' by force
    have full1 cdclW-bj U' V ∨ V = U'
    by (metis (lifting) full-unfold local.bj)
    then show ?thesis
    using ⟨cdclW-s'-without-decide** S U'⟩ by blast
  end
end

```

```

next
  case bj-prop note  $s' = \text{this}(1)$  and  $\text{bj-}T' = \text{this}(2)$  and  $T''\text{-}U = \text{this}(3)$ 
  have no-step  $\text{cdcl}_W\text{-cp } T'$ 
    using  $\text{bj-}T' \text{ full1-cdcl}_W\text{-bj-no-step-cdcl}_W\text{-bj}$  by blast
  moreover have full1  $\text{cdcl}_W\text{-cp } T'' U'$ 
    using  $\text{rtrancp-mono}[\text{of propagate } \text{cdcl}_W\text{-cp}] T''\text{-}U \text{ cdcl}_W\text{-cp.propagate' full1-U-U'}$ 
     $\text{rtrancp-full1I}[\text{of } \text{cdcl}_W\text{-cp } T'']$  by blast
  ultimately have  $\text{cdcl}_W\text{-s'-without-decide } T' U'$ 
    using  $\text{bj'-without-decide}[\text{of } T' T'' U'] \text{ bj-}T'$  by (simp add: full-unfold)
  then have  $\text{cdcl}_W\text{-s'-without-decide}^{**} S U'$ 
    using  $s' \text{ rtrancp.intros}(2)[\text{of - } S T' U']$  by blast
  then show ?thesis
    by (metis full-unfold local.bj rtrancp.rtrancp-refl)
qed
qed
qed

lemma rtrancp-cdclW-s'-without-decide-is-rtrancp-cdclW-merge-cp:
  assumes
     $\text{cdcl}_W\text{-s'-without-decide}^{**} S V$  and
    confl: conflicting  $S = C\text{-True}$ 
  shows
    ( $\text{cdcl}_W\text{-merge-cp}^{**} S V \wedge \text{conflicting } V = C\text{-True}$ )
     $\vee (\text{cdcl}_W\text{-merge-cp}^{**} S V \wedge \text{conflicting } V \neq C\text{-True} \wedge \text{no-step } \text{cdcl}_W\text{-cp } V \wedge \text{no-step } \text{cdcl}_W\text{-bj } V)$ 
     $\vee (\exists T. \text{cdcl}_W\text{-merge-cp}^{**} S T \wedge \text{conflict } T V)$ 
  using assms(1)
proof (induction)
  case base
  then show ?case using confl by auto
next
  case (step  $U V$ ) note  $st = \text{this}(1)$  and  $s = \text{this}(2)$  and  $IH = \text{this}(3)$ 
  from  $s$  show ?case
  proof (cases rule: cdclW-s'-without-decide.cases)
    case conflict'-without-decide
    then have  $rt: \text{cdcl}_W\text{-cp}^{++} U V$  unfolding full1-def by fast
    then have conflicting  $U = C\text{-True}$ 
      using  $\text{trancp-cdcl}_W\text{-cp-propagate-with-conflict-or-not}[\text{of } U V]$ 
      conflict by (auto dest!: trancpD simp: rtrancp-unfold)
    then have  $\text{cdcl}_W\text{-merge-cp}^{**} S U$  using IH by auto
    consider
      (propa)  $\text{propagate}^{++} U V$ 
      | (confl') conflict  $U V$ 
      | (propa-confl')  $U' \text{ where } \text{propagate}^{++} U U' \text{ conflict } U' V$ 
    using  $\text{trancp-cdcl}_W\text{-cp-propagate-with-conflict-or-not}[OF rt]$  unfolding rtrancp-unfold
    by fastforce
  then show ?thesis
  proof cases
    case propa
    then have  $\text{cdcl}_W\text{-merge-cp } U V$ 
      by auto
    moreover have conflicting  $V = C\text{-True}$ 
      using propa unfolding trancp-unfold-end by auto
    ultimately show ?thesis using  $\langle \text{cdcl}_W\text{-merge-cp}^{**} S U \rangle$  by force
  next

```

```

    case confl'
    then show ?thesis using ⟨cdclW-merge-cp** S U⟩ by auto
next
    case propa-confl' note propa = this(1) and confl' = this(2)
    then have cdclW-merge-cp U U' by auto
    then have cdclW-merge-cp** S U' using ⟨cdclW-merge-cp** S U⟩ by auto
    then show ?thesis using ⟨cdclW-merge-cp** S U⟩ confl' by auto
qed
next
case (bj'-without-decide U') note full-bj = this(1) and cp = this(3)
then have conflicting U ≠ C-True
  using full-bj unfolding full1-def by (fastforce dest!: tranclpD simp: cdclW-bj.simps)
with IH obtain T where
  S-T: cdclW-merge-cp** S T and T-U: conflict T U
  using full-bj unfolding full1-def by (blast dest: tranclpD)
then have cdclW-merge-cp T U'
  using cdclW-merge-cp.conflict'[of T U U'] full-bj by (simp add: full-unfold)
then have S-U': cdclW-merge-cp** S U' using S-T by auto
consider
  (n-s) U' = V
  | (propa) propagate++ U' V
  | (confl') conflict U' V
  | (propa-confl') U'' where propagate++ U' U'' conflict U'' V
  using tranclp-cdclW-cp-propagate-with-conflict-or-not cp
  unfolding rtranclp-unfold full-def by metis
then show ?thesis
proof cases
case propa
  then have cdclW-merge-cp U' V by auto
  moreover have conflicting V = C-True
    using propa unfolding tranclp-unfold-end by auto
  ultimately show ?thesis using S-U' by force
next
case confl'
  then show ?thesis using S-U' by auto
next
case propa-confl' note propa = this(1) and confl = this(2)
  have cdclW-merge-cp U' U'' using propa by auto
  then show ?thesis using S-U' confl by (meson rtranclp.rtrancl-into-rtrancl)
next
case n-s
  then show ?thesis
    using S-U' apply (cases conflicting V = C-True)
    using full-bj apply simp
    by (metis cp full-def full-unfold full-bj)
qed
qed
qed

```

lemma *no-step-cdcl_W-s'-no-ste-cdcl_W-merge-cp:*
assumes
cdcl_W-all-struct-inv S
conflicting S = C-True
no-step cdcl_W-s' S
shows *no-step cdcl_W-merge-cp S*

```

using assms apply (auto simp: cdclW-s'.simps cdclW-merge-cp.simps)
using conflict-is-full1-cdclW-cp apply blast
using cdclW-cp-normalized-element-all-inv cdclW-cp.propagate' by (metis cdclW-cp.propagate'
full-unfold tranclpD)

```

The *no-step decide S* is needed, since *cdcl_W-merge-cp* is *cdcl_W-s'* without *decide*.

lemma *conflicting-true-no-step-cdcl_W-merge-cp-no-step-s'-without-decide*:

```

assumes
  confl: conflicting S = C-True and
  inv: cdclW-M-level-inv S and
  n-s: no-step cdclW-merge-cp S
shows no-step cdclW-s'-without-decide S
proof (rule ccontr)
assume  $\neg$  no-step cdclW-s'-without-decide S
then obtain T where
  cdclW: cdclW-s'-without-decide S T
by auto
then have inv-T: cdclW-M-level-inv T
using rtranclp-cdclW-s'-without-decide-rtranclp-cdclW[of S T]
rtranclp-cdclW-consistent-inv inv by blast
from cdclW show False
proof cases
case conflict'-without-decide
have no-step propagate S
using n-s by blast
then have conflict S T
using local.conflict' tranclp-cdclW-cp-propagate-with-conflict-or-not[of S T]
unfolding full1-def by (metis full1-def local.conflict'-without-decide rtranclp-unfold
tranclp-unfold-begin)
moreover
then obtain T' where full cdclW-bj T T'
using cdclW-bj-exists-normal-form inv-T by blast
ultimately show False using cdclW-merge-cp.conflict' n-s by meson
next
case (bj'-without-decide S')
then show ?thesis
using confl unfolding full1-def by (fastforce simp: cdclW-bj.simps dest: tranclpD)
qed
qed

```

lemma *conflicting-true-no-step-s'-without-decide-no-step-cdcl_W-merge-cp*:

```

assumes
  inv: cdclW-all-struct-inv S and
  n-s: no-step cdclW-s'-without-decide S
shows no-step cdclW-merge-cp S
proof (rule ccontr)
assume  $\neg$  ?thesis
then obtain T where cdclW-merge-cp S T
by auto
then show False
proof cases
case (conflict' S')
then show False using n-s conflict'-without-decide conflict-is-full1-cdclW-cp by blast
next
case propagate'

```

moreover
 have $cdcl_W$ -all-struct-inv T
 using inv by (meson local.propagate' rtrancp-cdcl_W-all-struct-inv-inv
 rtrancp-propagate-is-rtrancp-cdcl_W trancp-into-rtrancp)
 then obtain U where full $cdcl_W$ -cp T U
 using $cdcl_W$ -cp-normalized-element-all-inv by auto
 ultimately have full1 $cdcl_W$ -cp S U
 using trancp-full-full1I[of $cdcl_W$ -cp S T U] $cdcl_W$ -cp.propagate'
 trancp-mono[of propagate $cdcl_W$ -cp] by blast
 then show False using conflict'-without-decide n -s by blast
qed
qed

lemma no-step-cdcl_W-merge-cp-no-step-cdcl_W-cp:
 $no_step\ cdcl_W\text{-merge-cp}\ S \implies cdcl_W\text{-M-level-inv}\ S \implies no_step\ cdcl_W\text{-cp}\ S$
 using $cdcl_W$ -bj-exists-normal-form $cdcl_W$ -consistent-inv[OF $cdcl_W$.conflict, of S]
 by (metis $cdcl_W$ -cp.cases $cdcl_W$ -merge-cp.simps trancp.intros(1))

lemma conflicting-not-true-rtrancp-cdcl_W-merge-cp-no-step-cdcl_W-bj:
 assumes
 conflicting $S = C\text{-True}$ and
 $cdcl_W$ -merge-cp** S T
 shows no-step $cdcl_W$ -bj T
 using assms(2,1) by (induction)
 (fastforce simp: $cdcl_W$ -merge-cp.simps full-def trancp-unfold-end $cdcl_W$ -bj.simps)+

lemma conflicting-true-full-cdcl_W-merge-cp-iff-full-cdcl_W-s'-without-decode:
 assumes
 confl: conflicting $S = C\text{-True}$ and
 inv: $cdcl_W$ -all-struct-inv S
 shows
 full $cdcl_W$ -merge-cp S $V \iff full\ cdcl_W$ -s'-without-decode S V (is ?fw \iff ?s')

proof
 assume ?fw
 then have st: $cdcl_W$ -merge-cp** S V and n -s: no-step $cdcl_W$ -merge-cp V
 unfolding full-def by blast+
 have inv-V: $cdcl_W$ -all-struct-inv V
 using rtrancp-cdcl_W-merge-cp-rtrancp-cdcl_W[of S V] (??fw) unfolding full-def
 by (simp add: inv rtrancp-cdcl_W-all-struct-inv-inv)
 consider
 (s') $cdcl_W$ -s'-without-decode** S V
 | (propa) T where $cdcl_W$ -s'-without-decode** S T and propagate⁺⁺ T V
 | (bj) T U where $cdcl_W$ -s'-without-decode** S T and full1 $cdcl_W$ -bj T U and propagate** U V
 using rtrancp-cdcl_W-merge-cp-is-rtrancp-cdcl_W-s'-without-decode confl st n -s by metis
 then have $cdcl_W$ -s'-without-decode** S V
proof cases
 case s'
 then show ?thesis .
next
 case propa note s' = this(1) and propa = this(2)
 have no-step $cdcl_W$ -cp V
 using no-step-cdcl_W-merge-cp-no-step-cdcl_W-cp n -s inv-V
 unfolding $cdcl_W$ -all-struct-inv-def by blast
 then have full1 $cdcl_W$ -cp T V
 using propa trancp-mono[of propagate $cdcl_W$ -cp] $cdcl_W$ -cp.propagate' unfolding full1-def


```

    by blast
  then have cdclW-s'-without-decide T V
    using conflict'-without-decide by blast
  then show ?thesis using s' by auto
next
case bj note s' = this(1) and bj = this(2) and propa = this(3)
have no-step cdclW-cp V
  using no-step-cdclW-merge-cp-no-step-cdclW-cp n-s inv-V
  unfolding cdclW-all-struct-inv-def by blast
then have full cdclW-cp U V
  using propa rtranclp-mono[of propagate cdclW-cp] cdclW-cp.propagate' unfolding full-def
  by blast
moreover have no-step cdclW-cp T
  using bj unfolding full1-def by (fastforce dest!: tranclpD simp:cdclW-bj.simps)
ultimately have cdclW-s'-without-decide T V
  using bj'-without-decide[of T U V] bj by blast
then show ?thesis using s' by auto
qed
moreover have no-step cdclW-s'-without-decide V
proof (cases conflicting V = C-True)
case False
{ fix ss :: 'st
  have ff1: ∀ s sa. ¬ cdclW-s' s sa ∨ full1 cdclW-cp s sa
    ∨ (∃ sb. decide s sb ∧ no-step cdclW-cp s ∧ full cdclW-cp sb sa)
    ∨ (∃ sb. full1 cdclW-bj s sb ∧ no-step cdclW-cp s ∧ full cdclW-cp sb sa)
    by (metis cdclW-s'.cases)
  have ff2: (∀ p s sa. ¬ full1 p (s::'st) sa ∨ p++ s sa ∧ no-step p sa)
    ∧ (∀ p s sa. (¬ p++ (s::'st) sa ∨ (∃ s. p sa s)) ∨ full1 p s sa)
    by (meson full1-def)
  obtain ssa :: ('st ⇒ 'st ⇒ bool) ⇒ 'st ⇒ 'st ⇒ 'st where
    ff3: ∀ p s sa. ¬ p++ s sa ∨ p s (ssa p s sa) ∧ p** (ssa p s sa) sa
    by (metis (no-types) tranclpD)
  then have a3: ¬ cdclW-cp++ V ss
    using False by (metis conflicting-clause-full-cdclW-cp full-def)
  have ∧s. ¬ cdclW-bj++ V s
    using ff3 False by (metis confl st
      conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj)
  then have ¬ cdclW-s'-without-decide V ss
    using ff1 a3 ff2 by (metis cdclW-s'-without-decide.cases)
}
then show ?thesis
  by fastforce
next
case True
  then show ?thesis
    using conflicting-true-no-step-cdclW-merge-cp-no-step-s'-without-decide n-s inv-V
    unfolding cdclW-all-struct-inv-def by blast
qed
ultimately show ?s' unfolding full-def by blast
next
assume s': ?s'
then have st: cdclW-s'-without-decide** S V and n-s: no-step cdclW-s'-without-decide V
  unfolding full-def by auto
then have cdclW** S V
  using rtranclp-cdclW-s'-without-decide-rtranclp-cdclW st by blast

```

then have $inv-V$: $cdcl_W$ -all-struct-inv V **using** inv $rtranclp$ - $cdcl_W$ -all-struct-inv-inv **by** $blast$
then have $n-s$ -cp- V : $no-step$ $cdcl_W$ -cp V
using $cdcl_W$ -cp-normalized-element-all-inv[of V] $full$ - $fullI$ [of $cdcl_W$ -cp V] $n-s$
 $conflict'$ -without-decide $conflicting$ -true- $no-step$ - s' -without-decide- $no-step$ - $cdcl_W$ -merge-cp
 $no-step$ - $cdcl_W$ -merge-cp- $no-step$ - $cdcl_W$ -cp
unfolding $cdcl_W$ -all-struct-inv-def **by** $presburger$
have $n-s$ -bj: $no-step$ $cdcl_W$ -bj V
proof ($rule$ $ccontr$)
assume \neg $?thesis$
then obtain W **where** W : $cdcl_W$ -bj V W **by** $blast$
have $cdcl_W$ -all-struct-inv W
using W $cdcl_W$. $simps$ $cdcl_W$ -all-struct-inv-inv $inv-V$ **by** $blast$
then obtain W' **where** $full1$ $cdcl_W$ -bj V W'
using $cdcl_W$ -bj-exists-normal-form[of W] $full$ - $fullI$ [of $cdcl_W$ -bj V W] W
unfolding $cdcl_W$ -all-struct-inv-def
by $blast$
moreover
then have $cdcl_W^{++}$ V W'
using $trancp$ -mono[of $cdcl_W$ -bj $cdcl_W$] $cdcl_W$.other $cdcl_W$ -o.bj **unfolding** $full1$ -def **by** $blast$
then have $cdcl_W$ -all-struct-inv W'
by ($meson$ $inv-V$ $rtranclp$ - $cdcl_W$ -all-struct-inv-inv $trancp$ -into- $rtranclp$)
then obtain X **where** $full$ $cdcl_W$ -cp W' X
using $cdcl_W$ -cp-normalized-element-all-inv **by** $blast$
ultimately show $False$
using bj' -without-decide $n-s$ -cp- V $n-s$ **by** $blast$
qed
from s' **consider**
 $(cp$ -true) $cdcl_W$ -merge-cp** S V **and** $conflicting$ $V = C$ -True
 $|$ $(cp$ -false) $cdcl_W$ -merge-cp** S V **and** $conflicting$ $V \neq C$ -True **and** $no-step$ $cdcl_W$ -cp V **and**
 $no-step$ $cdcl_W$ -bj V
 $|$ $(cp$ -confl) T **where** $cdcl_W$ -merge-cp** S T $conflict$ T V
using $rtranclp$ - $cdcl_W$ - s' -without-decide-is- $rtranclp$ - $cdcl_W$ -merge-cp[of S V] $confl$
unfolding $full$ -def **by** $blast$
then have $cdcl_W$ -merge-cp** S V
proof $cases$
case cp -confl **note** $S-T = this(1)$ **and** $conf-V = this(2)$
have $full$ $cdcl_W$ -bj V V
using $conf-V$ $n-s$ -bj **unfolding** $full$ -def **by** $fast$
then have $cdcl_W$ -merge-cp T V
using $cdcl_W$ -merge-cp. $conflict'$ $conf-V$ **by** $auto$
then show $?thesis$ **using** $S-T$ **by** $auto$
qed $fast+$
moreover
then have $cdcl_W^{**}$ S V **using** $rtranclp$ - $cdcl_W$ -merge-cp- $rtranclp$ - $cdcl_W$ **by** $blast$
then have $cdcl_W$ -all-struct-inv V
using inv $rtranclp$ - $cdcl_W$ -all-struct-inv-inv **by** $blast$
then have $no-step$ $cdcl_W$ -merge-cp V
using $conflicting$ -true- $no-step$ - s' -without-decide- $no-step$ - $cdcl_W$ -merge-cp s'
unfolding $full$ -def **by** $blast$
ultimately show $?fw$ **unfolding** $full$ -def **by** $auto$
qed
lemma $conflicting$ -true- $full1$ - $cdcl_W$ -merge-cp-iff- $full1$ - $cdcl_W$ - s' -without-decode:
assumes
 $confl$: $conflicting$ $S = C$ -True **and**

$inv: cdcl_W\text{-all-struct-inv } S$
shows
 $full1\ cdcl_W\text{-merge-cp } S\ V \longleftrightarrow full1\ cdcl_W\text{-s'-without-decide } S\ V$
proof –
have $full\ cdcl_W\text{-merge-cp } S\ V = full\ cdcl_W\text{-s'-without-decide } S\ V$
using $confl\ conflicting\text{-true-full-cdcl}_W\text{-merge-cp-iff-full-cdcl}_W\text{-s'-without-decode } inv$
by $blast$
then show $?thesis\ unfolding\ full\text{-unfold}\ full1\text{-def}$
by $(metis\ (mono\text{-tags})\ tranclp\text{-unfold-begin})$
qed

lemma $conflicting\text{-true-full1-cdcl}_W\text{-merge-cp-imp-full1-cdcl}_W\text{-s'-without-decode}:$
assumes
 $fw: full1\ cdcl_W\text{-merge-cp } S\ V$ **and**
 $inv: cdcl_W\text{-all-struct-inv } S$
shows
 $full1\ cdcl_W\text{-s'-without-decide } S\ V$
proof –
have $conflicting\ S = C\text{-True}$
using $fw\ unfolding\ full1\text{-def}\ by\ (auto\ dest!:\ tranclpD\ simp:\ cdcl_W\text{-merge-cp.simps})$
then show $?thesis$
using $conflicting\text{-true-full1-cdcl}_W\text{-merge-cp-iff-full1-cdcl}_W\text{-s'-without-decode } fw\ inv\ by\ blast$
qed

inductive $cdcl_W\text{-merge-stgy}\ where$
 $fw\text{-s-cp[intro]: } full1\ cdcl_W\text{-merge-cp } S\ T \implies cdcl_W\text{-merge-stgy } S\ T\ |$
 $fw\text{-s-decide[intro]: } decide\ S\ T \implies no\text{-step } cdcl_W\text{-merge-cp } S \implies full\ cdcl_W\text{-merge-cp } T\ U$
 $\implies cdcl_W\text{-merge-stgy } S\ U$

lemma $cdcl_W\text{-merge-stgy-tranclp-cdcl}_W\text{-merge}:$
assumes $fw: cdcl_W\text{-merge-stgy } S\ T$
shows $cdcl_W\text{-merge}^{++}\ S\ T$
proof –
{ fix $S\ T$
assume $full1\ cdcl_W\text{-merge-cp } S\ T$
then have $cdcl_W\text{-merge}^{++}\ S\ T$
using $tranclp\text{-mono}[of\ cdcl_W\text{-merge-cp } cdcl_W\text{-merge}^{++}]\ cdcl_W\text{-merge-cp-tranclp-cdcl}_W\text{-merge}$
unfolding $full1\text{-def}$
by $auto$
} note $full1\text{-cdcl}_W\text{-merge-cp-cdcl}_W\text{-merge} = this$
show $?thesis$
using fw
apply $(induction\ rule:\ cdcl_W\text{-merge-stgy.induct})$
using $full1\text{-cdcl}_W\text{-merge-cp-cdcl}_W\text{-merge}\ apply\ simp$
unfolding $full\text{-unfold}\ by\ (auto\ dest!:\ full1\text{-cdcl}_W\text{-merge-cp-cdcl}_W\text{-merge } fw\text{-decide})$
qed

lemma $rtranclp\text{-cdcl}_W\text{-merge-stgy-rtranclp-cdcl}_W\text{-merge}:$
assumes $fw: cdcl_W\text{-merge-stgy}^{**}\ S\ T$
shows $cdcl_W\text{-merge}^{**}\ S\ T$
using $fw\ cdcl_W\text{-merge-stgy-tranclp-cdcl}_W\text{-merge}\ rtranclp\text{-mono}[of\ cdcl_W\text{-merge-stgy } cdcl_W\text{-merge}^{++}]$
unfolding $tranclp\text{-rtranclp-rtranclp}\ by\ blast$

lemma $cdcl_W\text{-merge-stgy-rtranclp-cdcl}_W:$
 $cdcl_W\text{-merge-stgy } S\ T \implies cdcl_W^{**}\ S\ T$

apply (*induction rule: cdcl_W-merge-stgy.induct*)
using rtrancpl-cdcl_W-merge-cp-rtrancpl-cdcl_W **unfolding** full1-def
apply (*simp add: trancpl-into-rtrancpl*)
using rtrancpl-cdcl_W-merge-cp-rtrancpl-cdcl_W cdcl_W-o.decide cdcl_W.other **unfolding** full-def
by (*meson r-into-rtrancpl rtrancpl-trans*)

lemma rtrancpl-cdcl_W-merge-stgy-rtrancpl-cdcl_W:
 cdcl_W-merge-stgy^{**} S T \implies cdcl_W^{**} S T
using rtrancpl-mono[*of cdcl_W-merge-stgy cdcl_W^{**}*] cdcl_W-merge-stgy-rtrancpl-cdcl_W **by** auto

inductive cdcl_W-s'-w :: 'st \Rightarrow 'st \Rightarrow bool **where**
conflict': full1 cdcl_W-s'-without-decide S S' \implies cdcl_W-s'-w S S' |
decide': decide S S' \implies no-step cdcl_W-s'-without-decide S \implies full cdcl_W-s'-without-decide S' S''
 \implies cdcl_W-s'-w S S''

lemma cdcl_W-s'-w-rtrancpl-cdcl_W:
 cdcl_W-s'-w S T \implies cdcl_W^{**} S T
apply (*induction rule: cdcl_W-s'-w.induct*)
using rtrancpl-cdcl_W-s'-without-decide-rtrancpl-cdcl_W **unfolding** full1-def
apply (*simp add: trancpl-into-rtrancpl*)
using rtrancpl-cdcl_W-s'-without-decide-rtrancpl-cdcl_W **unfolding** full-def
by (*meson decide other rtrancpl-into-trancpl2 trancpl-into-rtrancpl*)

lemma rtrancpl-cdcl_W-s'-w-rtrancpl-cdcl_W:
 cdcl_W-s'-w^{**} S T \implies cdcl_W^{**} S T
using rtrancpl-mono[*of cdcl_W-s'-w cdcl_W^{**}*] cdcl_W-s'-w-rtrancpl-cdcl_W **by** auto

lemma no-step-cdcl_W-cp-no-step-cdcl_W-s'-without-decide:
assumes no-step cdcl_W-cp S **and** conflicting S = C-True **and** inv: cdcl_W-M-level-inv S
shows no-step cdcl_W-s'-without-decide S
by (*metis assms cdcl_W-cp.conflict' cdcl_W-cp.propagate' cdcl_W-merge-restart-cases trancplD*
conflicting-true-no-step-cdcl_W-merge-cp-no-step-s'-without-decide)

lemma no-step-cdcl_W-cp-no-step-cdcl_W-merge-restart:
assumes no-step cdcl_W-cp S **and** conflicting S = C-True
shows no-step cdcl_W-merge-cp S
by (*metis assms(1) cdcl_W-cp.conflict' cdcl_W-cp.propagate' cdcl_W-merge-restart-cases trancplD*)

lemma after-cdcl_W-s'-without-decide-no-step-cdcl_W-cp:
assumes cdcl_W-s'-without-decide S T
shows no-step cdcl_W-cp T
using assms **by** (*induction rule: cdcl_W-s'-without-decide.induct*) (*auto simp: full1-def full-def*)

lemma no-step-cdcl_W-s'-without-decide-no-step-cdcl_W-cp:
 cdcl_W-all-struct-inv S \implies no-step cdcl_W-s'-without-decide S \implies no-step cdcl_W-cp S
by (*simp add: conflicting-true-no-step-s'-without-decide-no-step-cdcl_W-merge-cp*
no-step-cdcl_W-merge-cp-no-step-cdcl_W-cp cdcl_W-all-struct-inv-def)

lemma after-cdcl_W-s'-w-no-step-cdcl_W-cp:
assumes cdcl_W-s'-w S T **and** cdcl_W-all-struct-inv S
shows no-step cdcl_W-cp T
using assms

proof (*induction rule: cdcl_W-s'-w.induct*)
case conflict'
then show ?case
by (*auto simp: full1-def trancpl-unfold-end after-cdcl_W-s'-without-decide-no-step-cdcl_W-cp*)

next
case (*decide'* S T U)
moreover
then have $cdcl_W^{**} S U$
using $rtrancpl-cdcl_W-s'-without-decide-rtrancpl-cdcl_W[of\ T\ U]\ cdcl_W.other[of\ S\ T]$
 $cdcl_W-o.decide$ **unfolding** *full-def* **by** *auto*
then have $cdcl_W-all-struct-inv\ U$
using $decide'.prems\ rtrancpl-cdcl_W-all-struct-inv-inv$ **by** *blast*
ultimately show *?case*
using $no-step-cdcl_W-s'-without-decide-no-step-cdcl_W-cp$ **unfolding** *full-def* **by** *blast*
qed

lemma $rtrancpl-cdcl_W-s'-w-no-step-cdcl_W-cp-or-eq$:
assumes $cdcl_W-s'-w^{**} S\ T$ **and** $cdcl_W-all-struct-inv\ S$
shows $S = T \vee no-step\ cdcl_W-cp\ T$
using *assms*
proof (*induction rule: rtrancpl-induct*)
case *base*
then show *?case* **by** *simp*
next
case (*step* $T\ U$)
moreover have $cdcl_W-all-struct-inv\ T$
using $rtrancpl-cdcl_W-s'-w-rtrancpl-cdcl_W[of\ S\ U]\ assms(2)\ rtrancpl-cdcl_W-all-struct-inv-inv$
 $rtrancpl-cdcl_W-s'-w-rtrancpl-cdcl_W\ step.hyps(1)$ **by** *blast*
ultimately show *?case* **using** $after-cdcl_W-s'-w-no-step-cdcl_W-cp$ **by** *fast*
qed

lemma $rtrancpl-cdcl_W-merge-stgy'-no-step-cdcl_W-cp-or-eq$:
assumes $cdcl_W-merge-stgy^{**} S\ T$ **and** $inv: cdcl_W-all-struct-inv\ S$
shows $S = T \vee no-step\ cdcl_W-cp\ T$
using *assms*
proof (*induction rule: rtrancpl-induct*)
case *base*
then show *?case* **by** *simp*
next
case (*step* $T\ U$)
moreover have $cdcl_W-all-struct-inv\ T$
using $rtrancpl-cdcl_W-merge-stgy-rtrancpl-cdcl_W[of\ S\ U]\ assms(2)\ rtrancpl-cdcl_W-all-struct-inv-inv$
 $rtrancpl-cdcl_W-s'-w-rtrancpl-cdcl_W\ step.hyps(1)$
by (*meson* $rtrancpl-cdcl_W-merge-stgy-rtrancpl-cdcl_W$)
ultimately show *?case*
using $after-cdcl_W-s'-w-no-step-cdcl_W-cp\ inv$ **unfolding** $cdcl_W-all-struct-inv-def$
by (*metis* $cdcl_W-all-struct-inv-def\ cdcl_W-merge-stgy.simps\ full1-def\ full-def$
 $no-step-cdcl_W-merge-cp-no-step-cdcl_W-cp\ rtrancpl-cdcl_W-all-struct-inv-inv$
 $rtrancpl-cdcl_W-merge-stgy-rtrancpl-cdcl_W\ trancpl.intros(1)\ trancpl-into-rtrancpl$)
qed

lemma $no-step-cdcl_W-s'-without-decide-no-step-cdcl_W-bj$:
assumes $no-step\ cdcl_W-s'-without-decide\ S$ **and** $inv: cdcl_W-all-struct-inv\ S$
shows $no-step\ cdcl_W-bj\ S$
proof (*rule ccontr*)
assume $\neg ?thesis$
then obtain T **where** $S-T: cdcl_W-bj\ S\ T$
by *auto*
have $cdcl_W-all-struct-inv\ T$

using $S \text{--} T \text{ cdcl}_W\text{--all-struct-inv-inv inv other}$ by *blast*
 then obtain T' where $\text{full1 cdcl}_W\text{--bj } S \ T'$
 using $\text{cdcl}_W\text{--bj-exists-normal-form}[of \ T] \ \text{full-fullI } S \text{--} T$ unfolding $\text{cdcl}_W\text{--all-struct-inv-def}$
 by *metis*
 moreover
 then have $\text{cdcl}_W^{**} \ S \ T'$
 using $\text{rtranclp-mono}[of \ \text{cdcl}_W\text{--bj } \text{cdcl}_W] \ \text{cdcl}_W.\text{other } \text{cdcl}_W\text{--o.bj } \text{tranclp-into-rtranclp}[of \ \text{cdcl}_W\text{--bj}]$
 unfolding full1-def by $(\text{metis } (\text{full-types}) \ \text{predicate2D } \text{predicate2I})$
 then have $\text{cdcl}_W\text{--all-struct-inv } T'$
 using $\text{inv } \text{rtranclp-cdcl}_W\text{--all-struct-inv-inv}$ by *blast*
 then obtain U where $\text{full cdcl}_W\text{--cp } T' \ U$
 using $\text{cdcl}_W\text{--cp-normalized-element-all-inv}$ by *blast*
 moreover have $\text{no-step cdcl}_W\text{--cp } S$
 using $S \text{--} T$ by $(\text{auto simp: cdcl}_W\text{--bj.simps})$
 ultimately show *False*
 using $\text{assms cdcl}_W\text{--s'-without-decide.intros}(2)[of \ S \ T' \ U]$ by *fast*
 qed

lemma $\text{cdcl}_W\text{--s'-w-no-step-cdcl}_W\text{--bj}$:
 assumes $\text{cdcl}_W\text{--s'-w } S \ T$ and $\text{cdcl}_W\text{--all-struct-inv } S$
 shows $\text{no-step cdcl}_W\text{--bj } T$
 using $\text{assms apply induction}$
 using $\text{rtranclp-cdcl}_W\text{--s'-without-decide-rtranclp-cdcl}_W \ \text{rtranclp-cdcl}_W\text{--all-struct-inv-inv}$
 $\text{no-step-cdcl}_W\text{--s'-without-decide-no-step-cdcl}_W\text{--bj}$ unfolding full1-def
 apply $(\text{meson tranclp-into-rtranclp})$
 using $\text{rtranclp-cdcl}_W\text{--s'-without-decide-rtranclp-cdcl}_W \ \text{rtranclp-cdcl}_W\text{--all-struct-inv-inv}$
 $\text{no-step-cdcl}_W\text{--s'-without-decide-no-step-cdcl}_W\text{--bj}$ unfolding full-def
 by $(\text{meson cdcl}_W\text{--merge-restart-cdcl}_W \ \text{fw-r-decide})$

lemma $\text{rtranclp-cdcl}_W\text{--s'-w-no-step-cdcl}_W\text{--bj-or-eq}$:
 assumes $\text{cdcl}_W\text{--s'-w}^{**} \ S \ T$ and $\text{cdcl}_W\text{--all-struct-inv } S$
 shows $S = T \vee \text{no-step cdcl}_W\text{--bj } T$
 using $\text{assms apply induction}$
 apply *simp*
 using $\text{rtranclp-cdcl}_W\text{--s'-w-rtranclp-cdcl}_W \ \text{rtranclp-cdcl}_W\text{--all-struct-inv-inv}$
 $\text{cdcl}_W\text{--s'-w-no-step-cdcl}_W\text{--bj}$ by *meson*

lemma $\text{rtranclp-cdcl}_W\text{--s'-no-step-cdcl}_W\text{--s'-without-decide-decomp-into-cdcl}_W\text{--merge}$:
 assumes
 $\text{cdcl}_W\text{--s'}^{**} \ R \ V$ and
 $\text{conflicting } R = C\text{--True}$ and
 $\text{inv: cdcl}_W\text{--all-struct-inv } R$
 shows $(\text{cdcl}_W\text{--merge-stgy}^{**} \ R \ V \wedge \text{conflicting } V = C\text{--True})$
 $\vee (\text{cdcl}_W\text{--merge-stgy}^{**} \ R \ V \wedge \text{conflicting } V \neq C\text{--True} \wedge \text{no-step cdcl}_W\text{--bj } V)$
 $\vee (\exists \ S \ T \ U. \text{cdcl}_W\text{--merge-stgy}^{**} \ R \ S \wedge \text{no-step cdcl}_W\text{--merge-cp } S \wedge \text{decide } S \ T$
 $\wedge \text{cdcl}_W\text{--merge-cp}^{**} \ T \ U \wedge \text{conflict } U \ V)$
 $\vee (\exists \ S \ T. \text{cdcl}_W\text{--merge-stgy}^{**} \ R \ S \wedge \text{no-step cdcl}_W\text{--merge-cp } S \wedge \text{decide } S \ T$
 $\wedge \text{cdcl}_W\text{--merge-cp}^{**} \ T \ V$
 $\wedge \text{conflicting } V = C\text{--True})$
 $\vee (\text{cdcl}_W\text{--merge-cp}^{**} \ R \ V \wedge \text{conflicting } V = C\text{--True})$
 $\vee (\exists \ U. \text{cdcl}_W\text{--merge-cp}^{**} \ R \ U \wedge \text{conflict } U \ V)$
 using $\text{assms}(1,2)$
proof *induction*
 case *base*
 then show *?case* by *simp*

```

next
case (step V W) note st = this(1) and s' = this(2) and IH = this(3)[OF this(4)] and
  n-s-R = this(4)
from s'
show ?case
proof cases
  case conflict'
  consider
    (s') cdclW-merge-stgy** R V
  | (dec-conf) S T U where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and
    decide S T and cdclW-merge-cp** T U and conflict U V
  | (dec) S T where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and decide S T
    and cdclW-merge-cp** T V and conflicting V = C-True
  | (cp) cdclW-merge-cp** R V
  | (cp-conf) U where cdclW-merge-cp** R U and conflict U V
  using IH by meson
then show ?thesis
proof cases
next
  case s'
  then have R = V
  by (metis full1-def inv local.conflict' tranclp-unfold-begin
    rtranclp-cdclW-merge-stgy'-no-step-cdclW-cp-or-eq)
  consider
    (V-W) V = W
  | (propa) propagate++ V W and conflicting W = C-True
  | (propa-conf) V' where propagate** V V' and conflict V' W
  using tranclp-cdclW-cp-propagate-with-conflict-or-not[of V W] conflict'
  unfolding full-unfold full1-def by blast
then show ?thesis
proof cases
  case V-W
  then show ?thesis using ⟨R = V⟩ n-s-R by simp
next
  case propa
  then show ?thesis using ⟨R = V⟩ by auto
next
  case propa-conf
  moreover
    then have cdclW-merge-cp** V V'
    by (metis Nitpick.rtranclp-unfold cdclW-merge-cp.propagate' r-into-rtranclp)
  ultimately show ?thesis using s' ⟨R = V⟩ by blast
qed
next
  case dec-conf note - = this(5)
  then have False using conflict' unfolding full1-def by (auto dest!: tranclpD)
  then show ?thesis by fast
next
  case dec note T-V = this(4)
  consider
    (propa) propagate++ V W and conflicting W = C-True
  | (propa-conf) V' where propagate** V V' and conflict V' W
  using tranclp-cdclW-cp-propagate-with-conflict-or-not[of V W] conflict'
  unfolding full1-def by blast
then show ?thesis

```

```

proof cases
  case propa
  then show ?thesis
    by (meson T-V cdclW-merge-cp.propagate' dec rtrancpl.rtrancpl-into-rtrancpl)
  next
  case propa-conf
  then have cdclW-merge-cp** T V'
    using T-V by (metis rtrancpl-unfold cdclW-merge-cp.propagate' rtrancpl.simps)
  then show ?thesis using dec propa-conf(2) by metis
  qed
next
  case cp
  consider
    (propa) propagate++ V W and conflicting W = C-True
    | (propa-conf) V' where propagate** V V' and conflict V' W
    using trancpl-cdclW-cp-propagate-with-conflict-or-not[of V W] conflict'
    unfolding full1-def by blast
  then show ?thesis
  proof cases
    case propa
    then show ?thesis by (meson cdclW-merge-cp.propagate' cp rtrancpl.rtrancpl-into-rtrancpl)
  next
    case propa-conf
    then show ?thesis
      using propa-conf(2) by (metis rtrancpl-unfold cdclW-merge-cp.propagate'
        cp rtrancpl.rtrancpl-into-rtrancpl)
    qed
  next
    case cp-conf
    then show ?thesis using conflict' unfolding full1-def by (fastforce dest!: trancplD)
  qed
next
  case (decide' V')
  then have conf-V: conflicting V = C-True
    by auto
  consider
    (s') cdclW-merge-stgy** R V
    | (dec-conf) S T U where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and
      decide S T and cdclW-merge-cp** T U and conflict U V
    | (dec) S T where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and decide S T
      and cdclW-merge-cp** T V and conflicting V = C-True
    | (cp) cdclW-merge-cp** R V
    | (cp-conf) U where cdclW-merge-cp** R U and conflict U V
  using IH by meson
  then show ?thesis
  proof cases
    case s'
    have conf-V': conflicting V' = C-True using decide'(1) by auto
    have full: full1 cdclW-cp V' W  $\vee$  (V' = W  $\wedge$  no-step cdclW-cp W)
      using decide'(3) unfolding full-unfold by blast
    consider
      (V'-W) V' = W
      | (propa) propagate++ V' W and conflicting W = C-True
      | (propa-conf) V'' where propagate** V' V'' and conflict V'' W
      using trancpl-cdclW-cp-propagate-with-conflict-or-not[of V W] decide'

```



```

by (metis ⟨full1 cdclW-cp V' W ∨ V' = W ∧ no-step cdclW-cp W⟩ full1-def
  tranclp-cdclW-cp-propagate-with-conflict-or-not)
then show ?thesis
proof cases
case V'-W
then show ?thesis
  using confl-V' local.decide'(1,2) s' conf-V
  no-step-cdclW-cp-no-step-cdclW-merge-restart by auto
next
case propa
then show ?thesis using local.decide'(1,2) s' by (metis cdclW-merge-cp.simps conf-V
  no-step-cdclW-cp-no-step-cdclW-merge-restart r-into-rtranclp)
next
case propa-confl
then have cdclW-merge-cp** V' V''
  by (metis rtranclp-unfold cdclW-merge-cp.propagate' r-into-rtranclp)
then show ?thesis
  using local.decide'(1,2) propa-confl(2) s' conf-V
  no-step-cdclW-cp-no-step-cdclW-merge-restart
  by metis
qed
next
case (dec) note s' = this(1) and dec = this(2) and cp = this(3) and ns-cp-T = this(4)
have full cdclW-merge-cp T V
  unfolding full-def by (simp add: conf-V local.decide'(2)
    no-step-cdclW-cp-no-step-cdclW-merge-restart ns-cp-T)
moreover have no-step cdclW-merge-cp V
  by (simp add: conf-V local.decide'(2) no-step-cdclW-cp-no-step-cdclW-merge-restart)
moreover have no-step cdclW-merge-cp S
  by (metis dec)
ultimately have cdclW-merge-stgy S V
  using cp by blast
then have cdclW-merge-stgy** R V using s' by auto
consider
  (V'-W) V' = W
  | (propa) propagate++ V' W and conflicting W = C-True
  | (propa-confl) V'' where propagate** V' V'' and conflict V'' W
  using tranclp-cdclW-cp-propagate-with-conflict-or-not[of V' W] decide'
  unfolding full-unfold full1-def by blast
then show ?thesis
proof cases
case V'-W
moreover have conflicting V' = C-True
  using decide'(1) by auto
ultimately show ?thesis
  using ⟨cdclW-merge-stgy** R V⟩ decide' ⟨no-step cdclW-merge-cp V⟩ by blast
next
case propa
moreover then have cdclW-merge-cp V' W
  by auto
ultimately show ?thesis
  using ⟨cdclW-merge-stgy** R V⟩ decide' ⟨no-step cdclW-merge-cp V⟩
  by (meson r-into-rtranclp)
next
case propa-confl

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    moreover then have  $cdcl_W\text{-merge-cp}^{**} V' V''$ 
      by (metis  $cdcl_W\text{-merge-cp.propagate}' rtranclp\text{-unfold tranclp-unfold-end}$ )
    ultimately show ?thesis using  $\langle cdcl_W\text{-merge-stgy}^{**} R V \rangle decide'$ 
       $\langle no\text{-step } cdcl_W\text{-merge-cp } V \rangle$  by (meson  $r\text{-into-rtranclp}$ )
  qed
next
case cp
have  $no\text{-step } cdcl_W\text{-merge-cp } V$ 
  using  $conf\text{-}V local.decide'(2) no\text{-step-cdcl}_W\text{-cp-no-step-cdcl}_W\text{-merge-restart}$  by blast
then have  $full\ cdcl_W\text{-merge-cp } R V$ 
  unfolding  $full\text{-def}$  using cp by fast
then have  $cdcl_W\text{-merge-stgy}^{**} R V$ 
  unfolding  $full\text{-unfold}$  by auto
have  $full1\ cdcl_W\text{-cp } V' W \vee (V' = W \wedge no\text{-step } cdcl_W\text{-cp } W)$ 
  using  $decide'(3) unfolding full\text{-unfold}$  by blast

consider
  ( $V' \text{-} W$ )  $V' = W$ 
| (propa)  $propagate^{++} V' W$  and conflicting  $W = C\text{-True}$ 
| (propa-conf)  $V''$  where  $propagate^{**} V' V''$  and conflict  $V'' W$ 
  using  $tranclp\text{-cdcl}_W\text{-cp-propagate-with-conflict-or-not}[of V' W] decide'$ 
  unfolding  $full\text{-unfold full1-def}$  by blast
then show ?thesis

proof cases
case  $V' \text{-} W$ 
moreover have  $conflicting V' = C\text{-True}$ 
  using  $decide'(1)$  by auto
ultimately show ?thesis
  using  $\langle cdcl_W\text{-merge-stgy}^{**} R V \rangle decide' \langle no\text{-step } cdcl_W\text{-merge-cp } V \rangle$  by blast
next
case propa
moreover then have  $cdcl_W\text{-merge-cp } V' W$ 
  by auto
ultimately show ?thesis using  $\langle cdcl_W\text{-merge-stgy}^{**} R V \rangle decide'$ 
   $\langle no\text{-step } cdcl_W\text{-merge-cp } V \rangle$  by (meson  $r\text{-into-rtranclp}$ )
next
case propa-conf
moreover then have  $cdcl_W\text{-merge-cp}^{**} V' V''$ 
  by (metis  $cdcl_W\text{-merge-cp.propagate}' rtranclp\text{-unfold tranclp-unfold-end}$ )
ultimately show ?thesis using  $\langle cdcl_W\text{-merge-stgy}^{**} R V \rangle decide'$ 
   $\langle no\text{-step } cdcl_W\text{-merge-cp } V \rangle$  by (meson  $r\text{-into-rtranclp}$ )
qed
next
case (dec-conf)
show ?thesis using  $conf\text{-}V dec-conf(5)$  by auto
next
case cp-conf
then show ?thesis using  $decide'$  by fastforce
qed
next
case ( $bj' V'$ )
then have  $\neg no\text{-step } cdcl_W\text{-bj } V$ 
  by (auto dest:  $tranclpD simp: full1\text{-def}$ )
then consider

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```

(s') cdclW-merge-stgy** R V and conflicting V = C-True
| (dec-confl) S T U where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and
  decide S T and cdclW-merge-cp** T U and conflict U V
| (dec) S T where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and decide S T
  and cdclW-merge-cp** T V and conflicting V = C-True
| (cp) cdclW-merge-cp** R V and conflicting V = C-True
| (cp-confl) U where cdclW-merge-cp** R U and conflict U V
using IH by meson
then show ?thesis
proof cases
  case s' note - = this(2)
  then have False
    using bj'(1) unfolding full1-def by (force dest!: tranclpD simp: cdclW-bj.simps)
  then show ?thesis by fast
next
  case dec note - = this(5)
  then have False
    using bj'(1) unfolding full1-def by (force dest!: tranclpD simp: cdclW-bj.simps)
  then show ?thesis by fast
next
  case dec-confl
  then have cdclW-merge-cp U V'
    using bj' cdclW-merge-cp.intros(1)[of U V V'] by (simp add: full-unfold)
  then have cdclW-merge-cp** T V'
    using dec-confl(4) by simp
  consider
    (V'-W) V' = W
  | (propa) propagate++ V' W and conflicting W = C-True
  | (propa-confl) V'' where propagate** V' V'' and conflict V'' W
  using tranclp-cdclW-cp-propagate-with-conflict-or-not[of V' W] bj'(3)
  unfolding full-unfold full1-def by blast
  then show ?thesis
  proof cases
    case V'-W
    then have no-step cdclW-cp V'
      using bj'(3) unfolding full-def by auto
    then have no-step cdclW-merge-cp V'
      by (metis cdclW-cp.propagate' cdclW-merge-cp.cases tranclpD
        no-step-cdclW-cp-no-conflict-no-propagate(1) )
    then have full1 cdclW-merge-cp T V'
      unfolding full1-def using ⟨cdclW-merge-cp U V'⟩ dec-confl(4) by auto
    then have full cdclW-merge-cp T V'
      by (simp add: full-unfold)
    then have cdclW-merge-stgy S V'
      using dec-confl(3) cdclW-merge-stgy.fw-s-decide ⟨no-step cdclW-merge-cp S⟩ by blast
    then have cdclW-merge-stgy** R V'
      using ⟨cdclW-merge-stgy** R S⟩ by auto
    show ?thesis
    proof cases
      assume conflicting W = C-True
      then show ?thesis using ⟨cdclW-merge-stgy** R V'⟩ ⟨V' = W⟩ by auto
    next
      assume conflicting W ≠ C-True
      then show ?thesis
        using ⟨cdclW-merge-stgy** R V'⟩ ⟨V' = W⟩ by (metis ⟨cdclW-merge-cp U V'⟩

```

```

      conflicting-not-true-rtrancp-cdclW-merge-cp-no-step-cdclW-bj dec-confl(5)
      r-into-rtrancp conflictE)
    qed
  next
    case propa
    moreover then have cdclW-merge-cp V' W
      by auto
    ultimately show ?thesis using decide' by (meson ⟨cdclW-merge-cp** T V'⟩ dec-confl(1-3)
      rtrancp.rtrancp-into-rtrancp)
  next
    case propa-confl
    moreover then have cdclW-merge-cp** V' V''
      by (metis cdclW-merge-cp.propagate' rtrancp-unfold trancp-unfold-end)
    ultimately show ?thesis by (meson ⟨cdclW-merge-cp** T V'⟩ dec-confl(1-3) rtrancp-trans)
  qed
next
  case cp note - = this(2)
  then show ?thesis using bj'(1) ⟨¬ no-step cdclW-bj V'⟩
    conflicting-not-true-rtrancp-cdclW-merge-cp-no-step-cdclW-bj by auto
next
  case cp-confl
  then have cdclW-merge-cp U V' by (simp add: cdclW-merge-cp.conflict' full-unfold
    local.bj'(1))
  consider
    (V'-W) V' = W
  | (propa) propagate++ V' W and conflicting W = C-True
  | (propa-confl) V'' where propagate** V' V'' and conflict V'' W
  using trancp-cdclW-cp-propagate-with-conflict-or-not[of V' W] bj'
  unfolding full-unfold full1-def by blast
  then show ?thesis

proof cases
  case V'-W
  show ?thesis
  proof cases
    assume conflicting V' = C-True
    then show ?thesis
      using V'-W ⟨cdclW-merge-cp U V'⟩ cp-confl(1) by force
  next
    assume confl: conflicting V' ≠ C-True
    then have no-step cdclW-merge-stgy V'
      by (auto simp: cdclW-merge-stgy.simps full1-def full-def cdclW-merge-cp.simps
        dest!: trancpD)
    have no-step cdclW-merge-cp V'
      using confl by (auto simp: full1-def full-def cdclW-merge-cp.simps
        dest!: trancpD)
    moreover have cdclW-merge-cp U W
      using V'-W ⟨cdclW-merge-cp U V'⟩ by blast
    ultimately have full1 cdclW-merge-cp R V'
      using cp-confl(1) V'-W unfolding full1-def by auto
    then have cdclW-merge-stgy R V'
      by auto
    moreover have no-step cdclW-merge-stgy V'
      using confl ⟨no-step cdclW-merge-cp V'⟩ by (auto simp: cdclW-merge-stgy.simps
        full1-def dest!: trancpD)

```

```

ultimately have  $cdcl_W\text{-merge-stgy}^{**} R V'$  by auto
show ?thesis by (metis  $V'-W \langle cdcl_W\text{-merge-cp } U V' \rangle \langle cdcl_W\text{-merge-stgy}^{**} R V' \rangle$ 
  conflicting-not-true-rtranclp-cdcl_W-merge-cp-no-step-cdcl_W-bj cp-confl(1)
  rtranclp.rtrancl-into-rtrancl step.premis)
qed
next
case propa
moreover then have  $cdcl_W\text{-merge-cp } V' W$ 
  by auto
ultimately show ?thesis using  $\langle cdcl_W\text{-merge-cp } U V' \rangle$  cp-confl(1) by force
next
case propa-confl
moreover then have  $cdcl_W\text{-merge-cp}^{**} V' V''$ 
  by (metis  $cdcl_W\text{-merge-cp.propagate}' rtranclp\text{-unfold tranclp-unfold-end}$ )
ultimately show ?thesis
  using  $\langle cdcl_W\text{-merge-cp } U V' \rangle$  cp-confl(1) by (metis rtranclp.rtrancl-into-rtrancl
    rtranclp-trans)
qed
qed
qed
qed

```

lemma $cdcl_W\text{-merge-stgy-cases}$ [consumes 1, case-names fw-s-cp fw-s-decide]:

```

assumes
   $cdcl_W\text{-merge-stgy } S U$ 
  full1  $cdcl_W\text{-merge-cp } S U \implies P$ 
   $\bigwedge T. \text{decide } S T \implies \text{no-step } cdcl_W\text{-merge-cp } S \implies \text{full } cdcl_W\text{-merge-cp } T U \implies P$ 
shows  $P$ 
using assms by (auto simp:  $cdcl_W\text{-merge-stgy.simps}$ )

```

lemma $decide\text{-rtranclp-cdcl}_W\text{-s}'\text{-rtranclp-cdcl}_W\text{-s}'$:

```

assumes
  dec:  $\text{decide } S T$  and
   $cdcl_W\text{-s}'^{**} T U$  and
  n-s-S:  $\text{no-step } cdcl_W\text{-cp } S$  and
   $\text{no-step } cdcl_W\text{-cp } U$ 
shows  $cdcl_W\text{-s}'^{**} S U$ 
using assms(2,4)

```

proof induction

```

case (step U V) note st = this(1) and s' = this(2) and IH = this(3) and n-s = this(4)
consider

```

```

  (TU)  $T = U$ 
  |  $(s'\text{-st}) T'$  where  $cdcl_W\text{-s}' T T'$  and  $cdcl_W\text{-s}'^{**} T' U$ 
  using st[unfolded rtranclp-unfold] by (auto dest!: tranclpD)

```

then show ?case

proof cases

case TU

then show ?thesis

proof –

```

have  $\forall p s sa. (\neg p^{++} (s::'st) sa \vee (\exists sb. p^{**} s sb \wedge p sb sa))$ 
   $\wedge ((\forall sb. \neg p^{**} s sb \vee \neg p sb sa) \vee p^{++} s sa)$ 
by (metis tranclp-unfold-end)

```

then obtain $ss :: ('st \Rightarrow 'st \Rightarrow \text{bool}) \Rightarrow 'st \Rightarrow 'st \Rightarrow 'st$ where

```

f2:  $\forall p s sa. (\neg p^{++} s sa \vee p^{**} s (ss p s sa) \wedge p (ss p s sa) sa)$ 
   $\wedge ((\forall sb. \neg p^{**} s sb \vee \neg p sb sa) \vee p^{++} s sa)$ 

```

```

    by maura
  have f3:  $cdcl_W-s' \ T \ V$ 
    using  $TU \ s'$  by blast
  moreover
  { assume  $\neg \ cdcl_W-s' \ S \ T$ 
    then have  $cdcl_W-s' \ S \ V$ 
      using f3 by (metis (no-types) assms(1,3)  $cdcl_W-s'.cases \ cdcl_W-s'.decide' \ full-unfold$ )
    then have  $cdcl_W-s'^{++} \ S \ V$ 
      by blast }
  ultimately have  $cdcl_W-s'^{++} \ S \ V$ 
    using f2 by (metis (full-types) rtrancp-unfold)
  then show ?thesis
    by simp
qed
next
case ( $s'-st \ T'$ ) note  $s'-T' = this(1)$  and  $st = this(2)$ 
have  $cdcl_W-s'^{**} \ S \ T'$ 
  using  $s'-T'$ 
  proof cases
    case conflict'
    then have  $cdcl_W-s' \ S \ T'$ 
      using dec  $cdcl_W-s'.decide' \ n-s-S$  by (simp add: full-unfold)
    then show ?thesis
      using st by auto
  next
    case ( $decide' \ T''$ )
    then have  $cdcl_W-s' \ S \ T$ 
      using dec  $cdcl_W-s'.decide' \ n-s-S$  by (simp add: full-unfold)
    then show ?thesis using  $decide' \ s'-T'$  by auto
  next
    case bj'
    then have False
      using dec unfolding full1-def by (fastforce dest!: trancpD simp:  $cdcl_W-bj.simps$ )
    then show ?thesis by fast
  qed
  then show ?thesis using  $s' \ st$  by auto
qed
next
case base
then have full  $cdcl_W-cp \ T \ T$ 
  by (simp add: full-unfold)
then show ?case
  using  $cdcl_W-s'.simps \ dec \ n-s-S$  by auto
qed

lemma rtrancp-cdcl_W-merge-stgy-rtrancp-cdcl_W-s':
  assumes
     $cdcl_W-merge-stgy^{**} \ R \ V$  and
     $inv: \ cdcl_W-all-struct-inv \ R$ 
  shows  $cdcl_W-s'^{**} \ R \ V$ 
  using assms(1)
proof induction
  case base
  then show ?case by simp
next

```

```

case (step S T) note st = this(1) and fw = this(2) and IH = this(3)
have cdclW-all-struct-inv S
  using inv rtrancpl-cdclW-all-struct-inv-inv rtrancpl-cdclW-merge-stgy-rtrancpl-cdclW st by blast
from fw show ?case
proof (cases rule: cdclW-merge-stgy-cases)
  case fw-s-cp
  then show ?thesis
  proof –
    assume a1: full1 cdclW-merge-cp S T
    obtain ss :: ('st ⇒ 'st ⇒ bool) ⇒ 'st ⇒ 'st where
      f2: ∧ p s sa pa sb sc sd pb se sf. (¬ full1 p (s::'st) sa ∨ p++ s sa)
        ∧ (¬ pa (sb::'st) sc ∨ ¬ full1 pa sd sb) ∧ (¬ pb++ se sf ∨ pb sf (ss pb sf)
          ∨ full1 pb se sf)
    by (metis (no-types) full1-def)
    then have f3: cdclW-merge-cp++ S T
    using a1 by auto
    obtain ssa :: ('st ⇒ 'st ⇒ bool) ⇒ 'st ⇒ 'st ⇒ 'st where
      f4: ∧ p s sa. ¬ p++ s sa ∨ p s (ssa p s sa)
    by (meson trancpl-unfold-begin)
    then have f5: ∧ s. ¬ full1 cdclW-merge-cp s S
    using f3 f2 by (metis (full-types))
    have ∧ s. ¬ full cdclW-merge-cp s S
    using f4 f3 by (meson full-def)
    then have S = R
    using f5 by (metis (no-types) cdclW-merge-stgy.simps rtrancpl-unfold st
      trancpl-unfold-end)
    then show ?thesis
    using f2 a1 by (metis (no-types) ⟨cdclW-all-struct-inv S⟩
      conflicting-true-full1-cdclW-merge-cp-imp-full1-cdclW-s'-without-decode
      rtrancpl-cdclW-s'-without-decide-rtrancpl-cdclW-s' rtrancpl-unfold)
  qed
next
case (fw-s-decide S') note dec = this(1) and n-S = this(2) and full = this(3)
moreover then have conflicting S' = C-True
  by auto
ultimately have full cdclW-s'-without-decide S' T
  by (meson ⟨cdclW-all-struct-inv S⟩ cdclW-merge-restart-cdclW fw-r-decide
    rtrancpl-cdclW-all-struct-inv-inv
    conflicting-true-full-cdclW-merge-cp-iff-full-cdclW-s'-without-decode)
then have a1: cdclW-s*** S' T
  unfolding full-def by (metis (full-types) rtrancpl-cdclW-s'-without-decide-rtrancpl-cdclW-s')
have cdclW-merge-stgy** S T
  using fw by blast
then have cdclW-s*** S T
  using decide-rtrancpl-cdclW-s'-rtrancpl-cdclW-s' a1 by (metis ⟨cdclW-all-struct-inv S⟩ dec
    n-S no-step-cdclW-merge-cp-no-step-cdclW-cp cdclW-all-struct-inv-def
    rtrancpl-cdclW-merge-stgy'-no-step-cdclW-cp-or-eq)
  then show ?thesis using IH by auto
qed
qed

```

lemma rtrancpl-cdcl_W-merge-stgy-distinct-mset-clauses:

assumes invR: cdcl_W-all-struct-inv R **and**
 st: cdcl_W-merge-stgy^{**} R S **and**
 dist: distinct-mset (clauses R) **and**

```

R: trail R = []
shows distinct-mset (clauses S)
using rtrancpl-cdclW-stgy-distinct-mset-clauses[OF invR - dist R]
invR st rtrancpl-mono[of cdclW-s' cdclW-stgy**] cdclW-s'-is-rtrancpl-cdclW-stgy
by (auto dest!: cdclW-s'-is-rtrancpl-cdclW-stgy rtrancpl-cdclW-merge-stgy-rtrancpl-cdclW-s')

lemma no-step-cdclW-s'-no-step-cdclW-merge-stgy:
  assumes
    inv: cdclW-all-struct-inv R and s': no-step cdclW-s' R
  shows no-step cdclW-merge-stgy R
proof -
  { fix ss :: 'st
    obtain ssa :: 'st ⇒ 'st ⇒ 'st where
      ff1: ∧s sa. ¬ cdclW-merge-stgy s sa ∨ full1 cdclW-merge-cp s sa ∨ decide s (ssa s sa)
      using cdclW-merge-stgy.cases by moura
    obtain ssb :: ('st ⇒ 'st ⇒ bool) ⇒ 'st ⇒ 'st ⇒ 'st where
      ff2: ∧p s sa. ¬ p++ s sa ∨ p s (ssb p s sa)
      by (meson trancpl-unfold-begin)
    obtain ssc :: 'st ⇒ 'st where
      ff3: ∧s sa sb. (¬ cdclW-all-struct-inv s ∨ ¬ cdclW-cp s sa ∨ cdclW-s' s (ssc s))
      ∧ (¬ cdclW-all-struct-inv s ∨ ¬ cdclW-o s sb ∨ cdclW-s' s (ssc s))
      using n-step-cdclW-stgy-iff-no-step-cdclW-cl-cdclW-o by moura
    then have ff4: ∧s. ¬ cdclW-o R s
      using s' inv by blast
    have ff5: ∧s. ¬ cdclW-cp++ R s
      using ff3 ff2 s' by (metis inv)
    have ∧s. ¬ cdclW-bj++ R s
      using ff4 ff2 by (metis bj)
    then have ∧s. ¬ cdclW-s'-without-decide R s
      using ff5 by (simp add: cdclW-s'-without-decide.simps full1-def)
    then have ¬ cdclW-s'-without-decide++ R ss
      using ff2 by blast
    then have ¬ cdclW-merge-stgy R ss
      using ff4 ff1 by (metis (full-types) decide full1-def inv
        conflicting-true-full1-cdclW-merge-cp-imp-full1-cdclW-s'-without-decode) }
    then show ?thesis
      by fastforce
  }
qed

lemma wf-cdclW-merge-cp:
  wf{(T, S). cdclW-all-struct-inv S ∧ cdclW-merge-cp S T}
  using wf-trancpl-cdclW-merge by (rule wf-subset) (auto simp: cdclW-merge-cp-trancpl-cdclW-merge)

lemma wf-cdclW-merge-stgy:
  wf{(T, S). cdclW-all-struct-inv S ∧ cdclW-merge-stgy S T}
  using wf-trancpl-cdclW-merge by (rule wf-subset)
  (auto simp add: cdclW-merge-stgy-trancpl-cdclW-merge)

lemma cdclW-merge-cp-obtain-normal-form:
  assumes inv: cdclW-all-struct-inv R
  obtains S where full cdclW-merge-cp R S
proof -
  obtain S where full (λS T. cdclW-all-struct-inv S ∧ cdclW-merge-cp S T) R S
  using wf-exists-normal-form-full[OF wf-cdclW-merge-cp] by blast
  then have

```


$st: (\lambda S T. \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-cp } S T)^{**} R S$ **and**
 $n\text{-s}: \text{no-step } (\lambda S T. \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-cp } S T) S$
unfolding full-def by blast+
have $\text{cdcl}_W\text{-merge-cp}^{**} R S$
using st **by induction auto**
moreover
have $\text{cdcl}_W\text{-all-struct-inv } S$
using st inv
apply ($\text{induction rule: rtrancp-induct}$)
apply $simp$
by ($\text{meson } r\text{-into-rtrancp } rtrancp\text{-cdcl}_W\text{-all-struct-inv-inv}$
 $rtrancp\text{-cdcl}_W\text{-merge-cp-rtrancp-cdcl}_W$)
then have $\text{no-step } \text{cdcl}_W\text{-merge-cp } S$
using $n\text{-s}$ **by auto**
ultimately show $?thesis$
using that unfolding full-def by blast
qed

lemma $\text{no-step-cdcl}_W\text{-merge-stgy-no-step-cdcl}_W\text{-s'}$:

assumes
 $inv: \text{cdcl}_W\text{-all-struct-inv } R$ **and**
 $confl: \text{conflicting } R = C\text{-True}$ **and**
 $n\text{-s}: \text{no-step } \text{cdcl}_W\text{-merge-stgy } R$
shows $\text{no-step } \text{cdcl}_W\text{-s'} R$
proof (rule ccontr)
assume $\neg ?thesis$
then obtain S **where** $\text{cdcl}_W\text{-s'} R S$ **by auto**
then show $False$
proof cases
case $conflict'$
then obtain S' **where** $\text{full1 } \text{cdcl}_W\text{-merge-cp } R S'$
by ($\text{metis (full-types) } \text{cdcl}_W\text{-merge-cp-obtain-normal-form } \text{cdcl}_W\text{-s'-without-decide.simps } confl$
 $\text{conflicting-true-no-step-cdcl}_W\text{-merge-cp-no-step-s'-without-decide full-def full-unfold } inv$
 $\text{cdcl}_W\text{-all-struct-inv-def}$)
then show $False$ **using** $n\text{-s}$ **by blast**
next
case ($decide' R'$)
then have $\text{cdcl}_W\text{-all-struct-inv } R'$
using inv $\text{cdcl}_W\text{-all-struct-inv-inv } \text{cdcl}_W\text{-other } \text{cdcl}_W\text{-o.decide}$ **by meson**
then obtain R'' **where** $\text{full } \text{cdcl}_W\text{-merge-cp } R' R''$
using $\text{cdcl}_W\text{-merge-cp-obtain-normal-form}$ **by blast**
moreover have $\text{no-step } \text{cdcl}_W\text{-merge-cp } R$
by ($\text{simp add: } confl \text{ local.decide' } (2) \text{ no-step-cdcl}_W\text{-cp-no-step-cdcl}_W\text{-merge-restart}$)
ultimately show $False$ **using** $n\text{-s } \text{cdcl}_W\text{-merge-stgy.intros local.decide' } (1)$ **by blast**
next
case ($bj' R'$)
then show $False$
using $confl \text{ no-step-cdcl}_W\text{-cp-no-step-cdcl}_W\text{-s'-without-decide } inv$
unfolding $\text{cdcl}_W\text{-all-struct-inv-def}$ **by blast**
qed
qed

lemma $\text{rtrancp-cdcl}_W\text{-merge-cp-no-step-cdcl}_W\text{-bj}$:

assumes $\text{conflicting } R = C\text{-True}$ **and** $\text{cdcl}_W\text{-merge-cp}^{**} R S$
shows $\text{no-step } \text{cdcl}_W\text{-bj } S$

```

using assms conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj by blast

lemma rtranclp-cdclW-merge-stgy-no-step-cdclW-bj:
  assumes confl: conflicting  $R = C\text{-True}$  and cdclW-merge-stgy**  $R S$ 
  shows no-step cdclW-bj  $S$ 
  using assms(2)
proof induction
  case base
  then show ?case
    using confl by (auto simp: cdclW-bj.simps)[]
next
  case (step  $S T$ ) note st = this(1) and fw = this(2) and IH = this(3)
  have confl-S: conflicting  $S = C\text{-True}$ 
    using fw apply cases
    by (auto simp: full1-def cdclW-merge-cp.simps dest!: tranclpD)
  from fw show ?case
    proof cases
      case fw-s-cp
      then show ?thesis
        using rtranclp-cdclW-merge-cp-no-step-cdclW-bj confl-S
        by (simp add: full1-def tranclp-into-rtranclp)
    next
      case (fw-s-decide  $S'$ )
      moreover then have conflicting  $S' = C\text{-True}$  by auto
      ultimately show ?thesis
        using conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj
        unfolding full-def by fast
    qed
  qed

lemma full-cdclW-s'-full-cdclW-merge-restart:
  assumes
    conflicting  $R = C\text{-True}$  and
    inv: cdclW-all-struct-inv  $R$ 
  shows full cdclW-s'  $R V \longleftrightarrow$  full cdclW-merge-stgy  $R V$  (is ?s'  $\longleftrightarrow$  ?fw)
proof
  assume ?s'
  then have cdclW-s'**  $R V$  unfolding full-def by blast
  have cdclW-all-struct-inv  $V$ 
    using ⟨cdclW-s'**  $R V$ ⟩ inv rtranclp-cdclW-all-struct-inv-inv rtranclp-cdclW-s'-rtranclp-cdclW
    by blast
  then have n-s: no-step cdclW-merge-stgy  $V$ 
    using no-step-cdclW-s'-no-step-cdclW-merge-stgy by (meson ⟨full cdclW-s'  $R V$ ⟩ full-def)
  have n-s-bj: no-step cdclW-bj  $V$ 
    by (metis ⟨cdclW-all-struct-inv  $V$ ⟩ ⟨full cdclW-s'  $R V$ ⟩ bj full-def
    n-step-cdclW-stgy-iff-no-step-cdclW-cl-cdclW-o)
  have n-s-cp: no-step cdclW-merge-cp  $V$ 
  proof -
    { fix ss :: 'st
      obtain ssa :: 'st  $\Rightarrow$  'st where
        ff1:  $\forall s. \neg$  cdclW-all-struct-inv  $s \vee$  cdclW-s'-without-decide  $s$  (ssa  $s$ )
         $\vee$  no-step cdclW-merge-cp  $s$ 
        using conflicting-true-no-step-s'-without-decide-no-step-cdclW-merge-cp by moura
      have ( $\forall p s sa. \neg$  full  $p$  (ss::'st)  $sa \vee p^{**} s sa \wedge$  no-step  $p sa$ ) and
        ( $\forall p s sa. (\neg p^{**} (ss::'st) sa \vee (\exists s. p sa s)) \vee$  full  $p s sa$ )
    }
  
```

```

    by (meson full-def)+
  then have  $\neg$  cdclW-merge-cp V ss
    using ff1 by (metis (no-types)  $\langle$ cdclW-all-struct-inv V $\rangle$   $\langle$ full cdclW-s' R V $\rangle$  cdclW-s'.simps
      cdclW-s'-without-decide.cases) }
  then show ?thesis
    by blast
qed
consider
  (fw-no-confl) cdclW-merge-stgy** R V and conflicting V = C-True
| (fw-confl) cdclW-merge-stgy** R V and conflicting V  $\neq$  C-True and no-step cdclW-bj V
| (fw-dec-confl) S T U where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and
  decide S T and cdclW-merge-cp** T U and conflict U V
| (fw-dec-no-confl) S T where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and
  decide S T and cdclW-merge-cp** T V and conflicting V = C-True
| (cp-no-confl) cdclW-merge-cp** R V and conflicting V = C-True
| (cp-confl) U where cdclW-merge-cp** R U and conflict U V
using rtranclp-cdclW-s'-no-step-cdclW-s'-without-decide-decomp-into-cdclW-merge[OF
   $\langle$ cdclW-s'** R V $\rangle$  assms] by auto
then show ?fw
proof cases
  case fw-no-confl
  then show ?thesis using n-s unfolding full-def by blast
next
  case fw-confl
  then show ?thesis using n-s unfolding full-def by blast
next
  case fw-dec-confl
  have cdclW-merge-cp U V
  using n-s-bj by (metis cdclW-merge-cp.simps full-unfold fw-dec-confl(5))
  then have full1 cdclW-merge-cp T V
  unfolding full1-def by (metis fw-dec-confl(4) n-s-cp tranclp-unfold-end)
  then have cdclW-merge-stgy S V using  $\langle$ decide S T $\rangle$   $\langle$ no-step cdclW-merge-cp S $\rangle$  by auto
  then show ?thesis using n-s  $\langle$  cdclW-merge-stgy** R S $\rangle$  unfolding full-def by auto
next
  case fw-dec-no-confl
  then have full cdclW-merge-cp T V
  using n-s-cp unfolding full-def by blast
  then have cdclW-merge-stgy S V using  $\langle$ decide S T $\rangle$   $\langle$ no-step cdclW-merge-cp S $\rangle$  by auto
  then show ?thesis using n-s  $\langle$  cdclW-merge-stgy** R S $\rangle$  unfolding full-def by auto
next
  case cp-no-confl
  then have full cdclW-merge-cp R V
  by (simp add: full-def n-s-cp)
  then have R = V  $\vee$  cdclW-merge-stgy++ R V
  by (metis (no-types) full-unfold fw-s-cp rtranclp-unfold tranclp-unfold-end)
  then show ?thesis
  by (simp add: full-def n-s rtranclp-unfold)
next
  case cp-confl
  have full cdclW-bj V V
  using n-s-bj unfolding full-def by blast
  then have full1 cdclW-merge-cp R V
  unfolding full1-def by (meson cdclW-merge-cp.conflict' cp-confl(1,2) n-s-cp
    rtranclp-into-tranclp1)
  then show ?thesis using n-s unfolding full-def by auto

```

```

qed
next
assume ?fw
then have  $cdcl_W^{**} R V$  using  $rtrancp\_mono[of\ cdcl_W\_merge\_stgy\ cdcl_W^{**}]$ 
 $cdcl_W\_merge\_stgy\_rtrancp\_cdcl_W$  unfolding full-def by auto
then have  $inv': cdcl_W\_all\_struct\_inv V$  using  $inv\ rtrancp\_cdcl_W\_all\_struct\_inv\_inv$  by blast
have  $cdcl_W\_s'^{**} R V$ 
using  $\langle ?fw \rangle$  by (simp add: full-def  $inv\ rtrancp\_cdcl_W\_merge\_stgy\_rtrancp\_cdcl_W\_s'$ )
moreover have no-step  $cdcl_W\_s' V$ 
proof cases
assume conflicting  $V = C\_True$ 
then show ?thesis
by (metis  $inv'$   $\langle full\ cdcl_W\_merge\_stgy\ R\ V \rangle$  full-def
no-step- $cdcl_W\_merge\_stgy\_no\_step\_cdcl_W\_s'$ )
next
assume  $confl\_V: conflicting\ V \neq C\_True$ 
then have no-step  $cdcl_W\_bj V$ 
using  $rtrancp\_cdcl_W\_merge\_stgy\_no\_step\_cdcl_W\_bj$  by (meson  $\langle full\ cdcl_W\_merge\_stgy\ R\ V \rangle$ 
assms(1) full-def)
then show ?thesis using  $confl\_V$  by (fastforce simp:  $cdcl_W\_s'.simps\ full1\_def\ cdcl_W\_cp.simps$ 
dest!:  $trancpD$ )
qed
ultimately show  $?s'$  unfolding full-def by blast
qed

```

```

lemma full- $cdcl_W\_stgy\_full\_cdcl_W\_merge$ :
assumes
 $conflicting\ R = C\_True$  and
 $inv: cdcl_W\_all\_struct\_inv R$ 
shows  $full\ cdcl_W\_stgy\ R\ V \longleftrightarrow full\ cdcl_W\_merge\_stgy\ R\ V$ 
by (simp add: assms(1) full- $cdcl_W\_s'-full\_cdcl_W\_merge\_restart\ full\_cdcl_W\_stgy\_iff\_full\_cdcl_W\_s'$ 
inv)

```

```

lemma full- $cdcl_W\_merge\_stgy\_final\_state\_conclusive'$ :
fixes  $S' :: 'st$ 
assumes full:  $full\ cdcl_W\_merge\_stgy\ (init\_state\ N)\ S'$ 
and no-d:  $distinct\_mset\_mset\ N$ 
shows ( $conflicting\ S' = C\_Clause\ \{\#\} \wedge unsatisfiable\ (set\_mset\ N)$ )
 $\vee (conflicting\ S' = C\_True \wedge trail\ S' \models_{asm}\ N \wedge satisfiable\ (set\_mset\ N))$ 
proof -
have  $cdcl_W\_all\_struct\_inv\ (init\_state\ N)$ 
using no-d unfolding  $cdcl_W\_all\_struct\_inv\_def$  by auto
moreover have  $conflicting\ (init\_state\ N) = C\_True$ 
by auto
ultimately show ?thesis
by (simp add: full full- $cdcl_W\_stgy\_final\_state\_conclusive\_from\_init\_state$ 
full- $cdcl_W\_stgy\_full\_cdcl_W\_merge\ no-d$ )
qed

```

end

19.5 Adding Restarts

```

locale  $cdcl_W\_ops\_restart =$ 
 $cdcl_W\_ops\ trail\ init\_clss\ learned\_clss\ backtrack\_lvl\ conflicting\ cons\_trail\ tl\_trail$ 
add-init-clss

```

```

add-learned-clss remove-clss update-backtrack-lvl update-conflicting init-state
restart-state
for
  trail :: 'st  $\Rightarrow$  ('v::linorder, nat, 'v clause) marked-lits and
  init-clss :: 'st  $\Rightarrow$  'v clauses and
  learned-clss :: 'st  $\Rightarrow$  'v clauses and
  backtrack-lvl :: 'st  $\Rightarrow$  nat and
  conflicting :: 'st  $\Rightarrow$  'v clause conflicting-clause and

  cons-trail :: ('v, nat, 'v clause) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-init-clss :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  add-learned-clss remove-clss :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  update-backtrack-lvl :: nat  $\Rightarrow$  'st  $\Rightarrow$  'st and
  update-conflicting :: 'v clause conflicting-clause  $\Rightarrow$  'st  $\Rightarrow$  'st and

  init-state :: 'v::linorder clauses  $\Rightarrow$  'st and
  restart-state :: 'st  $\Rightarrow$  'st +
fixes f :: nat  $\Rightarrow$  nat
assumes f: unbounded f
begin

```

The condition of the differences of cardinality has to be strict. Otherwise, you could be in a strange state, where nothing remains to do, but a restart is done. See the proof of well-foundedness.

inductive *cdcl_W-merge-with-restart* **where**

restart-step:

```

(cdclW-merge-stgy  $\sim$  (card (set-mset (learned-clss T)) - card (set-mset (learned-clss S)))) S T
 $\implies$  card (set-mset (learned-clss T)) - card (set-mset (learned-clss S)) > f n
 $\implies$  restart T U  $\implies$  cdclW-merge-with-restart (S, n) (U, Suc n) |

```

restart-full: full1 cdcl_W-merge-stgy S T \implies cdcl_W-merge-with-restart (S, n) (T, Suc n)

lemma *cdcl_W-merge-with-restart* S T \implies cdcl_W-merge-restart** (fst S) (fst T)

by (induction rule: *cdcl_W-merge-with-restart.induct*)

```

(auto dest!: relpowp-imp-rtranclp cdclW-merge-stgy-tranclp-cdclW-merge tranclp-into-rtranclp
  rtranclp-cdclW-merge-stgy-rtranclp-cdclW-merge rtranclp-cdclW-merge-tranclp-cdclW-merge-restart
  fw-r-rf cdclW-rf.restart
simp: full1-def)

```

lemma *cdcl_W-merge-with-restart-rtranclp-cdcl_W*:

cdcl_W-merge-with-restart S T \implies cdcl_W** (fst S) (fst T)

by (induction rule: *cdcl_W-merge-with-restart.induct*)

```

(auto dest!: relpowp-imp-rtranclp rtranclp-cdclW-merge-stgy-rtranclp-cdclW cdclW.rf
  cdclW-rf.restart tranclp-into-rtranclp simp: full1-def)

```

lemma *cdcl_W-merge-with-restart-increasing-number*:

cdcl_W-merge-with-restart S T \implies snd T = 1 + snd S

by (induction rule: *cdcl_W-merge-with-restart.induct*) auto

lemma full1 cdcl_W-merge-stgy S T \implies cdcl_W-merge-with-restart (S, n) (T, Suc n)

using *restart-full* **by** blast

lemma *cdcl_W-all-struct-inv-learned-clss-bound*:

assumes *inv*: cdcl_W-all-struct-inv S

shows set-mset (learned-clss S) \subseteq build-all-simple-clss (atms-of-msu (init-clss S))

proof
fix C
assume $C: C \in \text{set-mset } (\text{learned-clss } S)$
have $\text{distinct-mset } C$
using C **inv** **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ $\text{distinct-cdcl}_W\text{-state-def}$ $\text{distinct-mset-set-def}$
by auto
moreover **have** $\neg \text{tautology } C$
using C **inv** **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ $\text{cdcl}_W\text{-learned-clause-def}$ **by** auto
moreover
have $\text{atms-of } C \subseteq \text{atms-of-msu } (\text{learned-clss } S)$
using C **by** auto
then **have** $\text{atms-of } C \subseteq \text{atms-of-msu } (\text{init-clss } S)$
using inv **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ $\text{no-strange-atm-def}$ **by** force
moreover **have** $\text{finite } (\text{atms-of-msu } (\text{init-clss } S))$
using inv **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ **by** auto
ultimately **show** $C \in \text{build-all-simple-clss } (\text{atms-of-msu } (\text{init-clss } S))$
using $\text{distinct-mset-not-tautology-implies-in-build-all-simple-clss}$ $\text{build-all-simple-clss-mono}$
by blast
qed

lemma $\text{cdcl}_W\text{-merge-with-restart-init-clss}$:
 $\text{cdcl}_W\text{-merge-with-restart } S \ T \implies \text{cdcl}_W\text{-M-level-inv } (\text{fst } S) \implies$
 $\text{init-clss } (\text{fst } S) = \text{init-clss } (\text{fst } T)$
using $\text{cdcl}_W\text{-merge-with-restart-rtrancpl-cdcl}_W$ $\text{rtrancpl-cdcl}_W\text{-init-clss}$ **by** blast

lemma

$\text{wf } \{(T, S). \text{cdcl}_W\text{-all-struct-inv } (\text{fst } S) \wedge \text{cdcl}_W\text{-merge-with-restart } S \ T\}$

proof (rule ccontr)

assume $\neg ?thesis$

then **obtain** g **where**

$g: \bigwedge i. \text{cdcl}_W\text{-merge-with-restart } (g \ i) \ (g \ (\text{Suc } i))$ **and**

$\text{inv}: \bigwedge i. \text{cdcl}_W\text{-all-struct-inv } (\text{fst } (g \ i))$

unfolding $\text{wf-iff-no-infinite-down-chain}$ **by** fast

{ fix i

have $\text{init-clss } (\text{fst } (g \ i)) = \text{init-clss } (\text{fst } (g \ 0))$

apply ($\text{induction } i$)

apply simp

using g **inv** **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ **by** ($\text{metis } \text{cdcl}_W\text{-merge-with-restart-init-clss}$)

} note $\text{init-g} = \text{this}$

let $?S = g \ 0$

have $\text{finite } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S)))$

using inv **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ **by** auto

have $\text{snd-g}: \bigwedge i. \text{snd } (g \ i) = i + \text{snd } (g \ 0)$

apply ($\text{induct-tac } i$)

apply simp

by ($\text{metis } \text{Suc-eq-plus1-left add-Suc } \text{cdcl}_W\text{-merge-with-restart-increasing-number } g$)

then **have** $\text{snd-g-0}: \bigwedge i. i > 0 \implies \text{snd } (g \ i) = i + \text{snd } (g \ 0)$

by blast

have $\text{unbounded-f-g}: \text{unbounded } (\lambda i. f \ (\text{snd } (g \ i)))$

using f **unfolding** bounded-def **by** ($\text{metis } \text{add.commute } f \ \text{less-or-eq-imp-le } \text{snd-g}$

$\text{not-bounded-nat-exists-larger not-le ordered-cancel-comm-monoid-diff-class.le-iff-add}$)

obtain k **where**

$f\text{-g-k}: f \ (\text{snd } (g \ k)) > \text{card } (\text{build-all-simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$ **and**

$k > \text{card } (\text{build-all-simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$

using *not-bounded-nat-exists-larger*[*OF unbounded-f-g*] **by** *blast*

The following does not hold anymore with the non-strict version of cardinality in the definition.

```

{ fix i
  assume no-step cdclW-merge-stgy (fst (g i))
  with g[of i]
  have False
  proof (induction rule: cdclW-merge-with-restart.induct)
    case (restart-step T S n) note H = this(1) and c = this(2) and n-s = this(4)
    obtain S' where cdclW-merge-stgy S S'
      using H c by (metis gr-implies-not0 relpowp-E2)
    then show False using n-s by auto
  next
    case (restart-full S T)
    then show False unfolding full1-def by (auto dest: tranclpD)
  qed
} note H = this
obtain m T where
  m: m = card (set-mset (learned-clss T)) - card (set-mset (learned-clss (fst (g k)))) and
  m > f (snd (g k)) and
  restart T (fst (g (k+1))) and
  cdclW-merge-stgy: (cdclW-merge-stgy  $\sim$  m) (fst (g k)) T
  using g[of k] H[of Suc k] by (force simp: cdclW-merge-with-restart.simps full1-def)
have cdclW-merge-stgy** (fst (g k)) T
  using cdclW-merge-stgy relpowp-imp-rtranclp by metis
then have cdclW-all-struct-inv T
  using inv[of k] rtranclp-cdclW-all-struct-inv-inv rtranclp-cdclW-merge-stgy-rtranclp-cdclW
  by blast
moreover have card (set-mset (learned-clss T)) - card (set-mset (learned-clss (fst (g k))))
  > card (build-all-simple-clss (atms-of-msu (init-clss (fst ?S))))
  unfolding m[symmetric] using m > f (snd (g k)) f-g-k by linarith
then have card (set-mset (learned-clss T))
  > card (build-all-simple-clss (atms-of-msu (init-clss (fst ?S))))
  by linarith
moreover
  have init-clss (fst (g k)) = init-clss T
  using cdclW-merge-stgy** (fst (g k)) T rtranclp-cdclW-merge-stgy-rtranclp-cdclW
  rtranclp-cdclW-init-clss inv unfolding cdclW-all-struct-inv-def by blast
then have init-clss (fst ?S) = init-clss T
  using init-g[of k] by auto
ultimately show False
  using cdclW-all-struct-inv-learned-clss-bound by (metis Suc-leI card-mono not-less-eq-eq
    build-all-simple-clss-finite)
qed

lemma cdclW-merge-with-restart-distinct-mset-clauses:
assumes invR: cdclW-all-struct-inv (fst R) and
st: cdclW-merge-with-restart R S and
dist: distinct-mset (clauses (fst R)) and
R: trail (fst R) = []
shows distinct-mset (clauses (fst S))
using assms(2,1,3,4)
proof (induction)
case (restart-full S T)
then show ?case using rtranclp-cdclW-merge-stgy-distinct-mset-clauses[of S T] unfolding full1-def

```

```

    by (auto dest: tranclp-into-rtranclp)
next
case (restart-step T S n U)
then have distinct-mset (clauses T)
  using rtranclp-cdclW-merge-stgy-distinct-mset-clauses[of S T] unfolding full1-def
  by (auto dest: relpowp-imp-rtranclp)
then show ?case using (restart T U) by (metis clauses-restart distinct-mset-union fstI
  mset-le-exists-conv restart.cases state-eq-clauses)
qed

```

inductive *cdcl_W-with-restart* **where**

restart-step:

```

(cdclW-stgy  $\sim$  (card (set-mset (learned-clss T)) - card (set-mset (learned-clss S)))) S T  $\implies$ 
  card (set-mset (learned-clss T)) - card (set-mset (learned-clss S)) > f n  $\implies$ 
  restart T U  $\implies$ 
  cdclW-with-restart (S, n) (U, Suc n) |

```

restart-full: full1 cdcl_W-stgy S T \implies cdcl_W-with-restart (S, n) (T, Suc n)

lemma *cdcl_W-with-restart-rtranclp-cdcl_W*:

```

cdclW-with-restart S T  $\implies$  cdclW** (fst S) (fst T)
apply (induction rule: cdclW-with-restart.induct)
by (auto dest!: relpowp-imp-rtranclp tranclp-into-rtranclp fw-r-rf
  cdclW-rf.restart rtranclp-cdclW-stgy-rtranclp-cdclW cdclW-merge-restart-cdclW
  simp: full1-def)

```

lemma *cdcl_W-with-restart-increasing-number*:

```

cdclW-with-restart S T  $\implies$  snd T = 1 + snd S
by (induction rule: cdclW-with-restart.induct) auto

```

lemma full1 cdcl_W-stgy S T \implies cdcl_W-with-restart (S, n) (T, Suc n)

using restart-full **by** blast

lemma *cdcl_W-with-restart-init-clss*:

```

cdclW-with-restart S T  $\implies$  cdclW-M-level-inv (fst S)  $\implies$  init-clss (fst S) = init-clss (fst T)
using cdclW-with-restart-rtranclp-cdclW rtranclp-cdclW-init-clss by blast

```

lemma

wf {(T, S). cdcl_W-all-struct-inv (fst S) \wedge cdcl_W-with-restart S T}

proof (rule ccontr)

assume \neg ?thesis

then obtain g **where**

g: $\bigwedge i$. cdcl_W-with-restart (g i) (g (Suc i)) **and**

inv: $\bigwedge i$. cdcl_W-all-struct-inv (fst (g i))

unfolding wf-iff-no-infinite-down-chain **by** fast

{ **fix** i

have init-clss (fst (g i)) = init-clss (fst (g 0))

apply (induction i)

apply simp

using g inv **unfolding** cdcl_W-all-struct-inv-def **by** (metis cdcl_W-with-restart-init-clss)

} **note** init-g = this

let ?S = g 0

have finite (atms-of-msu (init-clss (fst ?S)))

using inv **unfolding** cdcl_W-all-struct-inv-def **by** auto

have snd-g: $\bigwedge i$. snd (g i) = i + snd (g 0)

apply (induct-tac i)


```

  apply simp
  by (metis Suc-eq-plus1-left add-Suc cdclW-with-restart-increasing-number g)
then have snd-g-0:  $\bigwedge i. i > 0 \implies \text{snd } (g \ i) = i + \text{snd } (g \ 0)$ 
  by blast
have unbounded-f-g:  $\text{unbounded } (\lambda i. f \ (\text{snd } (g \ i)))$ 
  using f unfolding bounded-def by (metis add.commute f less-or-eq-imp-le snd-g
    not-bounded-nat-exists-larger not-le ordered-cancel-comm-monoid-diff-class.le-iff-add)

obtain k where
  f-g-k:  $f \ (\text{snd } (g \ k)) > \text{card } (\text{build-all-simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$  and
  k >  $\text{card } (\text{build-all-simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$ 
  using not-bounded-nat-exists-larger[OF unbounded-f-g] by blast

```

The following does not hold anymore with the non-strict version of cardinality in the definition.

```

{ fix i
  assume no-step cdclW-stgy (fst (g i))
  with g[of i]
  have False
    proof (induction rule: cdclW-with-restart.induct)
      case (restart-step T S n) note H = this(1) and c = this(2) and n-s = this(4)
      obtain S' where cdclW-stgy S S'
        using H c by (metis gr-implies-not0 relpowp-E2)
      then show False using n-s by auto
    next
      case (restart-full S T)
      then show False unfolding full1-def by (auto dest: tranclpD)
    qed
  } note H = this
obtain m T where
  m:  $m = \text{card } (\text{set-mset } (\text{learned-clss } T)) - \text{card } (\text{set-mset } (\text{learned-clss } (\text{fst } (g \ k))))$  and
  m >  $f \ (\text{snd } (g \ k))$  and
  restart T (fst (g (k+1))) and
  cdclW-merge-stgy:  $(\text{cdcl}_W\text{-stgy } \rightsquigarrow m) \ (\text{fst } (g \ k)) \ T$ 
  using g[of k] H[of Suc k] by (force simp: cdclW-with-restart.simps full1-def)
have cdclW-stgy** (fst (g k)) T
  using cdclW-merge-stgy relpowp-imp-rtranclp by metis
then have cdclW-all-struct-inv T
  using inv[of k] rtranclp-cdclW-all-struct-inv-inv rtranclp-cdclW-stgy-rtranclp-cdclW by blast
moreover have  $\text{card } (\text{set-mset } (\text{learned-clss } T)) - \text{card } (\text{set-mset } (\text{learned-clss } (\text{fst } (g \ k))))$ 
  >  $\text{card } (\text{build-all-simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$ 
  unfolding m[symmetric] using m > f (snd (g k)) f-g-k by linarith
then have  $\text{card } (\text{set-mset } (\text{learned-clss } T))$ 
  >  $\text{card } (\text{build-all-simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$ 
  by linarith
moreover
  have  $\text{init-clss } (\text{fst } (g \ k)) = \text{init-clss } T$ 
    using cdclW-stgy** (fst (g k)) T rtranclp-cdclW-stgy-rtranclp-cdclW rtranclp-cdclW-init-clss
    inv unfolding cdclW-all-struct-inv-def
    by blast
  then have  $\text{init-clss } (\text{fst } ?S) = \text{init-clss } T$ 
    using init-g[of k] by auto
ultimately show False
  using cdclW-all-struct-inv-learned-clss-bound by (metis Suc-leI card-mono not-less-eq-eq
    build-all-simple-clss-finite)
qed

```

```

lemma cdclW-with-restart-distinct-mset-clauses:
  assumes invR: cdclW-all-struct-inv (fst R) and
  st: cdclW-with-restart R S and
  dist: distinct-mset (clauses (fst R)) and
  R: trail (fst R) = []
  shows distinct-mset (clauses (fst S))
  using assms(2,1,3,4)
proof (induction)
  case (restart-full S T)
  then show ?case using rtrancpl-cdclW-stgy-distinct-mset-clauses[of S T] unfolding full1-def
    by (auto dest: trancpl-into-rtrancpl)
next
  case (restart-step T S n U)
  then have distinct-mset (clauses T) using rtrancpl-cdclW-stgy-distinct-mset-clauses[of S T]
    unfolding full1-def by (auto dest: relpowp-imp-rtrancpl)
  then show ?case using (restart T U) by (metis clauses-restart distinct-mset-union fstI
    mset-le-exists-conv restart.cases state-eq-clauses)
qed
end

locale luby-sequence =
  fixes ur :: nat
  assumes ur > 0
begin

lemma exists-luby-decomp:
  fixes i :: nat
  shows  $\exists k :: \text{nat}. (2^{k-1} \leq i \wedge i < 2^k - 1) \vee i = 2^k - 1$ 
proof (induction i)
  case 0
  then show ?case
    by (rule exI[of - 0], simp)
next
  case (Suc n)
  then obtain k where  $2^{k-1} \leq n \wedge n < 2^k - 1 \vee n = 2^k - 1$ 
    by blast
  then consider
    (st-interv)  $2^{k-1} \leq n$  and  $n \leq 2^k - 2$ 
  | (end-interv)  $2^{k-1} \leq n$  and  $n = 2^k - 2$ 
  | (pow2)  $n = 2^k - 1$ 
  by linarith
  then show ?case
  proof cases
    case st-interv
    then show ?thesis apply — apply (rule exI[of - k])
      by (metis (no-types, lifting) One-nat-def Suc-diff-Suc Suc-lessI
         $\langle 2^{k-1} \leq n \wedge n < 2^k - 1 \vee n = 2^k - 1 \rangle$  diff-self-eq-0
        dual-order.trans le-SucI le-imp-less-Suc numeral-2-eq-2 one-le-numeral
        one-le-power zero-less-numeral zero-less-power)
    case end-interv
    then show ?thesis apply — apply (rule exI[of - k]) by auto
  next
  case pow2

```

then show *?thesis* apply – apply (rule *exI*[*of* - *k*+1]) by auto
 qed
 qed

Luby sequences are defined by:

- $2^k - 1$, if $i = (2::'a)^k - (1::'a)$
- *luby-sequence-core* ($i - 2^{k-1} + 1$), if $(2::'a)^{k-1} \leq i$ and $i \leq (2::'a)^k - (1::'a)$

Then the sequence is then scaled by a constant unit run (called *ur* here), strictly positive.

function *luby-sequence-core* :: *nat* \Rightarrow *nat* **where**

luby-sequence-core *i* =

(if $\exists k. i = 2^k - 1$

then $2^{((\text{SOME } k. i = 2^k - 1) - 1)}$

else *luby-sequence-core* ($i - 2^{((\text{SOME } k. 2^{(k-1)} \leq i \wedge i < 2^k - 1) - 1) + 1}$))

by *auto*

termination

proof (*relation less-than*, *goal-cases*)

case 1

then show *?case* **by** *auto*

next

case ($2\ i$)

let $?k = (\text{SOME } k. 2^{(k-1)} \leq i \wedge i < 2^k - 1)$

have $2^{(?k-1)} \leq i \wedge i < 2^{?k} - 1$

apply (rule *someI-ex*)

using *2 exists-luby-decomp* **by** *blast*

then show *?case*

proof –

have $\forall n\ na. \neg (1::nat) \leq n \vee 1 \leq n \wedge na$

by (*meson one-le-power*)

then have $f1: (1::nat) \leq 2^{(?k-1)}$

using *one-le-numeral* **by** *blast*

have $f2: i - 2^{(?k-1)} + 2^{(?k-1)} = i$

using $2^{(?k-1)} \leq i \wedge i < 2^{?k} - 1$ *le-add-diff-inverse2* **by** *blast*

have $f3: 2^{?k} - 1 \neq \text{Suc } 0$

using $f1$ $2^{(?k-1)} \leq i \wedge i < 2^{?k} - 1$ **by** *linarith*

have $2^{?k} - (1::nat) \neq 0$

using $2^{(?k-1)} \leq i \wedge i < 2^{?k} - 1$ *gr-implies-not0* **by** *blast*

then have $f4: 2^{?k} \neq (1::nat)$

by *linarith*

have $f5: \forall n\ na. \text{ if } na = 0 \text{ then } (n::nat) \wedge na = 1 \text{ else } n \wedge na = n * n \wedge (na - 1)$

by (*simp add: power-eq-if*)

then have $?k \neq 0$

using $f4$ **by** *meson*

then have $2^{(?k-1)} \neq \text{Suc } 0$

using $f5\ f3$ **by** *presburger*

then have $\text{Suc } 0 < 2^{(?k-1)}$

using $f1$ **by** *linarith*

then show *?thesis*

using $f2$ *less-than-iff* **by** *presburger*

qed

qed

declare *luby-sequence-core.simps*[*simp del*]

lemma *two-pover-n-eq-two-power-n'-eq*:

assumes $H: (2::nat) \wedge (k::nat) - 1 = 2 \wedge k' - 1$

shows $k' = k$

proof –

have $(2::nat) \wedge (k::nat) = 2 \wedge k'$

using H **by** (*metis One-nat-def Suc-pred zero-less-numeral zero-less-power*)

then show *?thesis* **by** *simp*

qed

lemma *luby-sequence-core-two-power-minus-one*:

luby-sequence-core $(2^k - 1) = 2^{(k-1)}$ (**is** *?L = ?K*)

proof –

have *decomp*: $\exists ka. 2^k - 1 = 2^{ka} - 1$

by *auto*

have $?L = 2^{((SOME k'. (2::nat) \wedge k - 1 = 2^{k'} - 1) - 1)}$

apply (*subst luby-sequence-core.simps, subst decomp*)

by *simp*

moreover have $(SOME k'. (2::nat) \wedge k - 1 = 2^{k'} - 1) = k$

apply (*rule some-equality*)

apply *simp*

using *two-pover-n-eq-two-power-n'-eq* **by** *blast*

ultimately show *?thesis* **by** *presburger*

qed

lemma *different-luby-decomposition-false*:

assumes

$H: 2 \wedge (k - Suc\ 0) \leq i$ **and**

$k': i < 2 \wedge k' - Suc\ 0$ **and**

$k-k': k > k'$

shows *False*

proof –

have $2 \wedge k' - Suc\ 0 < 2 \wedge (k - Suc\ 0)$

using $k-k'$ *less-eq-Suc-le* **by** *auto*

then show *?thesis*

using $H\ k'$ **by** *linarith*

qed

lemma *luby-sequence-core-not-two-power-minus-one*:

assumes

$k-i: 2 \wedge (k - 1) \leq i$ **and**

$i-k: i < 2^k - 1$

shows *luby-sequence-core* $i = \text{luby-sequence-core } (i - 2 \wedge (k - 1) + 1)$

proof –

have $H: \neg (\exists ka. i = 2^{ka} - 1)$

proof (*rule ccontr*)

assume $\neg ?thesis$

then obtain $k': nat$ **where** $k': i = 2^{k'} - 1$ **by** *blast*

have $(2::nat) \wedge k' - 1 < 2^k - 1$

using $i-k$ *unfolding* k' .

then have $(2::nat) \wedge k' < 2^k$

by *linarith*

then have $k' < k$

by *simp*

```

have  $2^{\wedge} (k - 1) \leq 2^{\wedge} k' - (1::nat)$ 
  using k-i unfolding k' .
then have  $(2::nat)^{\wedge} (k-1) < 2^{\wedge} k'$ 
  by (metis Suc-diff-1 not-le not-less-eq zero-less-numeral zero-less-power)
then have  $k-1 < k'$ 
  by simp

show False using  $\langle k' < k \rangle \langle k-1 < k' \rangle$  by linarith
qed
have  $\bigwedge k k'. 2^{\wedge} (k - Suc\ 0) \leq i \implies i < 2^{\wedge} k - Suc\ 0 \implies 2^{\wedge} (k' - Suc\ 0) \leq i \implies$ 
 $i < 2^{\wedge} k' - Suc\ 0 \implies k = k'$ 
  by (meson different-luby-decomposition-false linorder-neqE-nat)
then have k:  $(SOME\ k. 2^{\wedge} (k - Suc\ 0) \leq i \wedge i < 2^{\wedge} k - Suc\ 0) = k$ 
  using k-i i-k by auto
show ?thesis
  apply (subst luby-sequence-core.simps[of i], subst H)
  by (simp add: k)
qed

lemma unbounded-luby-sequence-core: unbounded luby-sequence-core
  unfolding bounded-def
proof
  assume  $\exists b. \forall n. \text{luby-sequence-core } n \leq b$ 
  then obtain b where b:  $\bigwedge n. \text{luby-sequence-core } n \leq b$ 
    by metis
  have luby-sequence-core  $(2^{\wedge}(b+1) - 1) = 2^{\wedge}b$ 
    using luby-sequence-core-two-power-minus-one[of b+1] by simp
  moreover have  $(2::nat)^{\wedge}b > b$ 
    by (induction b) auto
  ultimately show False using b[of  $2^{\wedge}(b+1) - 1$ ] by linarith
qed

abbreviation luby-sequence :: nat  $\Rightarrow$  nat where
luby-sequence n  $\equiv$  ur * luby-sequence-core n

lemma bounded-luby-sequence: unbounded luby-sequence
  using bounded-const-product[of ur] luby-sequence-axioms
  luby-sequence-def unbounded-luby-sequence-core by blast

lemma luby-sequence-core-0: luby-sequence-core 0 = 1
proof -
  have 0:  $(0::nat) = 2^{\wedge}0 - 1$ 
    by auto
  show ?thesis
    by (subst 0, subst luby-sequence-core-two-power-minus-one) simp
qed

lemma luby-sequence-core n  $\geq$  1
proof (induction n rule: nat-less-induct-case)
  case 0
  then show ?case by (simp add: luby-sequence-core-0)
next
  case (Suc n) note IH = this

  consider

```

```

    (interv) k where  $2^{\wedge} (k - 1) \leq \text{Suc } n$  and  $\text{Suc } n < 2^{\wedge} k - 1$ 
  | (pow2) k where  $\text{Suc } n = 2^{\wedge} k - \text{Suc } 0$ 
using exists-luby-decomp[of Suc n] by auto

then show ?case
proof cases
  case pow2
  show ?thesis
    using luby-sequence-core-two-power-minus-one pow2 by auto
  next
  case interv
  have n:  $\text{Suc } n - 2^{\wedge} (k - 1) + 1 < \text{Suc } n$ 
  by (metis Suc-1 Suc-eq-plus1 add.commute add-diff-cancel-left' add-less-mono1 gr0I
    interv(1) interv(2) le-add-diff-inverse2 less-Suc-eq not-le power-0 power-one-right
    power-strict-increasing-iff)
  show ?thesis
    apply (subst luby-sequence-core-not-two-power-minus-one[OF interv])
    using IH n by auto
qed
qed
end

locale luby-sequence-restart =
  luby-sequence ur +
  cdclW-ops trail init-clss learned-clss backtrack-lvl conflicting cons-trail tl-trail
  add-init-clss
  add-learned-clss remove-clss update-backtrack-lvl update-conflicting init-state
  restart-state
for
  ur :: nat and
  trail :: 'st  $\Rightarrow$  ('v::linorder, nat, 'v clause) marked-lits and
  init-clss :: 'st  $\Rightarrow$  'v clauses and
  learned-clss :: 'st  $\Rightarrow$  'v clauses and
  backtrack-lvl :: 'st  $\Rightarrow$  nat and
  conflicting :: 'st  $\Rightarrow$  'v clause conflicting-clause and
  cons-trail :: ('v, nat, 'v clause) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-init-clss :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  add-learned-clss remove-clss :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  update-backtrack-lvl :: nat  $\Rightarrow$  'st  $\Rightarrow$  'st and
  update-conflicting :: 'v clause conflicting-clause  $\Rightarrow$  'st  $\Rightarrow$  'st and

  init-state :: 'v::linorder clauses  $\Rightarrow$  'st and
  restart-state :: 'st  $\Rightarrow$  'st
begin

sublocale cdclW-ops-restart - - - - - luby-sequence
  apply unfold-locales
  using bounded-luby-sequence by blast

end

end
theory CDCL-W-Incremental
imports CDCL-W-Termination

```

begin

20 Incremental SAT solving

context *cdcl_W-ops*
begin

This invariant holds all the invariant related to the strategy. See the structural invariant in *cdcl_W-all-struct-inv*

definition *cdcl_W-stgy-invariant* **where**

cdcl_W-stgy-invariant $S \longleftrightarrow$
 $\text{conflict-is-false-with-level } S$
 $\wedge \text{no-clause-is-false } S$
 $\wedge \text{no-smaller-confl } S$
 $\wedge \text{no-clause-is-false } S$

lemma *cdcl_W-stgy-cdcl_W-stgy-invariant*:

assumes

cdcl_W: *cdcl_W-stgy* S T **and**
inv-s: *cdcl_W-stgy-invariant* S **and**
inv: *cdcl_W-all-struct-inv* S

shows

cdcl_W-stgy-invariant T

unfolding *cdcl_W-stgy-invariant-def* *cdcl_W-all-struct-inv-def* **apply** *standard*

apply (rule *cdcl_W-stgy-ex-lit-of-max-level*[of S])

using *assms* **unfolding** *cdcl_W-stgy-invariant-def* *cdcl_W-all-struct-inv-def* **apply** *auto*[7]

apply *standard*

using *cdcl_W* *cdcl_W-stgy-not-non-negated-init-clss* **apply** *blast*

apply *standard*

apply (rule *cdcl_W-stgy-no-smaller-confl-inv*)

using *assms* **unfolding** *cdcl_W-stgy-invariant-def* *cdcl_W-all-struct-inv-def* **apply** *auto*[4]

using *cdcl_W* *cdcl_W-stgy-not-non-negated-init-clss* **by** *auto*

lemma *rtrancpl-cdcl_W-stgy-cdcl_W-stgy-invariant*:

assumes

cdcl_W: *cdcl_W-stgy*^{**} S T **and**
inv-s: *cdcl_W-stgy-invariant* S **and**
inv: *cdcl_W-all-struct-inv* S

shows

cdcl_W-stgy-invariant T

using *assms* **apply** (*induction*)

apply *simp*

using *cdcl_W-stgy-cdcl_W-stgy-invariant* *rtrancpl-cdcl_W-all-struct-inv-inv*

rtrancpl-cdcl_W-stgy-rtrancpl-cdcl_W **by** *blast*

abbreviation *decr-bt-lvl* **where**

decr-bt-lvl $S \equiv \text{update-backtrack-lvl } (\text{backtrack-lvl } S - 1) S$

When we add a new clause, we reduce the trail until we get to the first literal included in C . Then we can mark the conflict.

fun *cut-trail-wrt-clause* **where**

cut-trail-wrt-clause $C \sqcap S = S \mid$

cut-trail-wrt-clause C (*Marked* $L - \# M$) $S =$

(if $-L \in \# C$ then S

$\text{else cut-trail-wrt-clause } C \ M \ (\text{decr-bt-lvl } (\text{tl-trail } S))) \mid$
 $\text{cut-trail-wrt-clause } C \ (\text{Propagated } L - \# \ M) \ S =$
 $(\text{if } -L \in \# \ C \ \text{then } S$
 $\text{else cut-trail-wrt-clause } C \ M \ (\text{tl-trail } S))$

definition $\text{add-new-clause-and-update} :: 'v \text{ literal multiset} \Rightarrow 'st \Rightarrow 'st$ **where**
 $\text{add-new-clause-and-update } C \ S =$
 $(\text{if trail } S \models_{\text{as}} C \text{Not } C$
 $\text{then update-conflicting } (C \text{-Clause } C) \ (\text{add-init-cls } C \ (\text{cut-trail-wrt-clause } C \ (\text{trail } S) \ S))$
 $\text{else add-init-cls } C \ S)$

thm $\text{cut-trail-wrt-clause.induct}$

lemma $\text{init-clss-cut-trail-wrt-clause[simp]}:$
 $\text{init-clss } (\text{cut-trail-wrt-clause } C \ M \ S) = \text{init-clss } S$
by $(\text{induction rule: cut-trail-wrt-clause.induct}) \text{ auto}$

lemma $\text{learned-clss-cut-trail-wrt-clause[simp]}:$
 $\text{learned-clss } (\text{cut-trail-wrt-clause } C \ M \ S) = \text{learned-clss } S$
by $(\text{induction rule: cut-trail-wrt-clause.induct}) \text{ auto}$

lemma $\text{conflicting-clss-cut-trail-wrt-clause[simp]}:$
 $\text{conflicting } (\text{cut-trail-wrt-clause } C \ M \ S) = \text{conflicting } S$
by $(\text{induction rule: cut-trail-wrt-clause.induct}) \text{ auto}$

lemma $\text{trail-cut-trail-wrt-clause}:$

$\exists M. \text{ trail } S = M \ @ \ \text{trail } (\text{cut-trail-wrt-clause } C \ (\text{trail } S) \ S)$
proof $(\text{induction trail } S \text{ arbitrary:S rule: marked-lit-list-induct})$
 case nil
 $\text{then show ?case by simp}$
next
 $\text{case } (\text{marked } L \ l \ M) \ \text{note } IH = \text{this}(1)[\text{of } \text{decr-bt-lvl } (\text{tl-trail } S)] \ \text{and } M = \text{this}(2)[\text{symmetric}]$
 $\text{then show ?case using Cons-eq-appendI by fastforce+}$
next
 $\text{case } (\text{proped } L \ l \ M) \ \text{note } IH = \text{this}(1)[\text{of } (\text{tl-trail } S)] \ \text{and } M = \text{this}(2)[\text{symmetric}]$
 $\text{then show ?case using Cons-eq-appendI by fastforce+}$
qed

lemma $\text{n-dup-no-dup-trail-cut-trail-wrt-clause[simp]}:$
 $\text{assumes } n\text{-d: no-dup } (\text{trail } T)$
 $\text{shows no-dup } (\text{trail } (\text{cut-trail-wrt-clause } C \ (\text{trail } T) \ T))$
proof $-$
 $\text{obtain } M \ \text{where}$
 $M: \text{ trail } T = M \ @ \ \text{trail } (\text{cut-trail-wrt-clause } C \ (\text{trail } T) \ T)$
 $\text{using trail-cut-trail-wrt-clause[of } T \ C] \ \text{by auto}$
 show ?thesis
 $\text{using } n\text{-d unfolding arg-cong[OF } M, \text{ of no-dup}] \ \text{by auto}$
qed

lemma $\text{cut-trail-wrt-clause-backtrack-lvl-length-marked}:$

assumes
 $\text{backtrack-lvl } T = \text{length } (\text{get-all-levels-of-marked } (\text{trail } T))$
 shows
 $\text{backtrack-lvl } (\text{cut-trail-wrt-clause } C \ (\text{trail } T) \ T) =$
 $\text{length } (\text{get-all-levels-of-marked } (\text{trail } (\text{cut-trail-wrt-clause } C \ (\text{trail } T) \ T)))$
 using assms


```

proof (induction trail T arbitrary:T rule: marked-lit-list-induct)
  case nil
  then show ?case by simp
next
  case (marked L l M) note IH = this(1)[of decr-bt-lvl (tl-trail T)] and M = this(2)[symmetric]
  and bt = this(3)
  then show ?case by auto
next
  case (proped L l M) note IH = this(1)[of tl-trail T] and M = this(2)[symmetric] and bt = this(3)
  then show ?case by auto
qed

```

lemma cut-trail-wrt-clause-get-all-levels-of-marked:

assumes get-all-levels-of-marked (trail T) = rev [Suc 0..
 Suc (length (get-all-levels-of-marked (trail T)))]

shows

get-all-levels-of-marked (trail ((cut-trail-wrt-clause C (trail T) T))) = rev [Suc 0..
 Suc (length (get-all-levels-of-marked (trail ((cut-trail-wrt-clause C (trail T) T)))))]

using assms

proof (induction trail T arbitrary:T rule: marked-lit-list-induct)

case nil

then show ?case **by** simp

next

case (marked L l M) **note** IH = this(1)[of decr-bt-lvl (tl-trail T)] **and** M = this(2)[symmetric]
and bt = this(3)

then show ?case **by** (cases count C L = 0) auto

next

case (proped L l M) **note** IH = this(1)[of tl-trail T] **and** M = this(2)[symmetric] **and** bt = this(3)
then show ?case **by** (cases count C L = 0) auto

qed

lemma cut-trail-wrt-clause-CNot-trail:

assumes trail T \models_{as} CNot C

shows

(trail ((cut-trail-wrt-clause C (trail T) T))) \models_{as} CNot C

using assms

proof (induction trail T arbitrary:T rule: marked-lit-list-induct)

case nil

then show ?case **by** simp

next

case (marked L l M) **note** IH = this(1)[of decr-bt-lvl (tl-trail T)] **and** M = this(2)[symmetric]
and bt = this(3)

then show ?case **apply** (cases count C (-L) = 0)

apply (auto simp: true-annots-true-cl)

by (smt CNot-def One-nat-def count-single diff-Suc-1 in-CNot-uminus less-numeral-extra(4)
 marked.prem marked-lit.sel(1) mem-Collect-eq true-annot-def true-annot-lit-of-notin-skip
 true-annots-def true-clss-def zero-less-diff)

next

case (proped L l M) **note** IH = this(1)[of tl-trail T] **and** M = this(2)[symmetric] **and** bt = this(3)
then show ?case

apply (cases count C (-L) = 0)

apply (auto simp: true-annots-true-cl)

by (smt CNot-def One-nat-def count-single diff-Suc-1 in-CNot-uminus less-numeral-extra(4))

*proped.premis marked-lit.sel(2) mem-Collect-eq true-annot-def true-annot-lit-of-notin-skip
true-annot-def true-clss-def zero-less-diff)*
qed

lemma *cut-trail-wrt-clause-hd-trail-in-or-empty-trail:*

$((\forall L \in \#C. -L \notin \text{lit-of } (\text{trail } T)) \wedge \text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T) = [])$
 $\vee (-\text{lit-of } (\text{hd } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T))) \in \#C$
 $\wedge \text{length } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T)) \geq 1)$

using *assms*

proof (*induction trail T arbitrary:T rule: marked-lit-list-induct*)

case *nil*

then show ?*case by simp*

next

case (*marked L l M*) **note** *IH = this(1)[of decr-bt-lvl (tl-trail T)] and M = this(2)[symmetric]*

then show ?*case by simp force*

next

case (*proped L l M*) **note** *IH = this(1)[of tl-trail T] and M = this(2)[symmetric]*

then show ?*case by simp force*

qed

We can fully run *cdcl_W*-s or add a clause. Remark that we use *cdcl_W*-s to avoid an explicit *skip*, *resolve*, and *backtrack* normalisation to get rid of the conflict *C* if possible.

inductive *incremental-cdcl_W :: 'st \Rightarrow 'st \Rightarrow bool for S where*

add-conf:

trail S \models_{asm} init-clss S \Rightarrow distinct-mset C \Rightarrow conflicting S = C-True \Rightarrow

trail S \models_{as} CNot C \Rightarrow

full cdcl_W-stgy

(update-conflicting (C-Clause C) (add-init-cls C (cut-trail-wrt-clause C (trail S) S))) T \Rightarrow
incremental-cdcl_W S T |

add-no-conf:

trail S \models_{asm} init-clss S \Rightarrow distinct-mset C \Rightarrow conflicting S = C-True \Rightarrow

\neg trail S \models_{as} CNot C \Rightarrow

full cdcl_W-stgy (add-init-cls C S) T \Rightarrow

incremental-cdcl_W S T

inductive *add-learned-clss :: 'st \Rightarrow 'v clauses \Rightarrow 'st \Rightarrow bool for S :: 'st where*

add-learned-clss-nil: add-learned-clss S {#} S |

add-learned-clss-plus:

add-learned-clss S A T \Rightarrow add-learned-clss S ({#x#} + A) (add-learned-clss x T)

declare *add-learned-clss.intros[intro]*

lemma *Ex-add-learned-clss:*

$\exists T. \text{add-learned-clss } S A T$

by (*induction A arbitrary: S rule: multiset-induct*) (*auto simp: union-commute[of - {#-#}]*)

lemma *add-learned-clss-trail:*

assumes *add-learned-clss S U T and no-dup (trail S)*

shows *trail T = trail S*

using *assms by (induction rule: add-learned-clss.induct) (simp-all add: ac-simps)*

lemma *add-learned-clss-learned-clss:*

assumes *add-learned-clss S U T and no-dup (trail S)*

shows *learned-clss T = U + learned-clss S*

using *assms by (induction rule: add-learned-clss.induct)*

(auto simp: ac-simps dest: add-learned-clss-trail)

lemma *add-learned-clss-init-clss*:
assumes *add-learned-clss S U T and no-dup (trail S)*
shows *init-clss T = init-clss S*
using *assms by (induction rule: add-learned-clss.induct)*
(auto simp: ac-simps dest: add-learned-clss-trail)

lemma *add-learned-clss-conflicting*:
assumes *add-learned-clss S U T and no-dup (trail S)*
shows *conflicting T = conflicting S*
using *assms by (induction rule: add-learned-clss.induct)*
(auto simp: ac-simps dest: add-learned-clss-trail)

lemma *add-learned-clss-backtrack-lvl*:
assumes *add-learned-clss S U T and no-dup (trail S)*
shows *backtrack-lvl T = backtrack-lvl S*
using *assms by (induction rule: add-learned-clss.induct)*
(auto simp: ac-simps dest: add-learned-clss-trail)

lemma *add-learned-clss-init-state-mempty[dest!]*:
add-learned-clss (init-state N) {#} T \implies T = init-state N
by *(cases rule: add-learned-clss.cases) (auto simp: add-learned-clss.cases)*

For multiset larger than 1 element, there is no way to know in which order the clauses are added.
But contrary to a definition *fold-mset*, there is an element.

lemma *add-learned-clss-init-state-single[dest!]*:
add-learned-clss (init-state N) {#C#} T \implies T = add-learned-clss C (init-state N)
by *(induction {#C#} T rule: add-learned-clss.induct)*
(auto simp: add-learned-clss.cases ac-simps union-is-single split: split-if-asm)

thm *rtrancp-cdcl_W-stgy-no-smaller-conflict-inv cdcl_W-stgy-final-state-conclusive*

lemma *cdcl_W-all-struct-inv-add-new-clause-and-update-cdcl_W-all-struct-inv*:

assumes
inv-T: cdcl_W-all-struct-inv T and
tr-T-N[simp]: trail T \models_{asm} N and
tr-C[simp]: trail T \models_{as} CNot C and
[simp]: distinct-mset C

shows *cdcl_W-all-struct-inv (add-new-clause-and-update C T) (is cdcl_W-all-struct-inv ?T')*

proof –

let *?T = update-conflicting (C-Clause C) (add-init-clss C (cut-trail-wrt-clause C (trail T) T))*

obtain *M where*

M: trail T = M @ trail (cut-trail-wrt-clause C (trail T) T)

using *trail-cut-trail-wrt-clause[of T C] by blast*

have *H[dest]: $\bigwedge x. x \in \text{ lits-of } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T)) \implies x \in \text{ lits-of } (\text{trail } T)$*

using *inv-T arg-cong[OF M, of lits-of] by auto*

have *H'[dest]: $\bigwedge x. x \in \text{ set } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T)) \implies x \in \text{ set } (\text{trail } T)$*

using *inv-T arg-cong[OF M, of set] by auto*

have *H-proped: $\bigwedge x. x \in \text{ set } (\text{get-all-mark-of-propagated } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T))) \implies x \in \text{ set } (\text{get-all-mark-of-propagated } (\text{trail } T))$*

using *inv-T arg-cong[OF M, of get-all-mark-of-propagated] by auto*

have *[simp]: no-strange-atm ?T*

using *inv-T unfolding cdcl_W-all-struct-inv-def no-strange-atm-def add-new-clause-and-update-def*

```

cdclW-M-level-inv-def
by (auto dest!: H H')

have M-lev: cdclW-M-level-inv T
  using inv-T unfolding cdclW-all-struct-inv-def by blast
then have no-dup (M @ trail (cut-trail-wrt-clause C (trail T) T))
  unfolding cdclW-M-level-inv-def unfolding M[symmetric] by auto
then have [simp]: no-dup (trail (cut-trail-wrt-clause C (trail T) T))
  by auto

have consistent-interp (lits-of (M @ trail (cut-trail-wrt-clause C (trail T) T)))
  using M-lev unfolding cdclW-M-level-inv-def unfolding M[symmetric] by auto
then have [simp]: consistent-interp (lits-of (trail (cut-trail-wrt-clause C (trail T) T)))
  unfolding consistent-interp-def by auto

have [simp]: cdclW-M-level-inv ?T
  unfolding cdclW-M-level-inv-def apply (auto dest: H H')
  simp: M-lev cdclW-M-level-inv-def cut-trail-wrt-clause-backtrack-lvl-length-marked)
  using M-lev cut-trail-wrt-clause-get-all-levels-of-marked[of T C]
  by (auto simp: cdclW-M-level-inv-def cut-trail-wrt-clause-backtrack-lvl-length-marked)

have [simp]:  $\bigwedge s. s \in \# \text{learned-clss } T \implies \neg \text{tautology } s$ 
  using inv-T unfolding cdclW-all-struct-inv-def by auto

have distinct-cdclW-state T
  using inv-T unfolding cdclW-all-struct-inv-def by auto
then have [simp]: distinct-cdclW-state ?T
  unfolding distinct-cdclW-state-def by auto

have cdclW-conflicting T
  using inv-T unfolding cdclW-all-struct-inv-def by auto
have trail ?T  $\models_{as}$  CNot C
  by (simp add: cut-trail-wrt-clause-CNot-trail)
then have [simp]: cdclW-conflicting ?T
  unfolding cdclW-conflicting-def apply simp
  by (metis M  $\langle$ cdclW-conflicting T $\rangle$  append-assoc cdclW-conflicting-decomp(2))

have decomp-T: all-decomposition-implies-m (init-clss T) (get-all-marked-decomposition (trail T))
  using inv-T unfolding cdclW-all-struct-inv-def by auto
have all-decomposition-implies-m (init-clss ?T)
  (get-all-marked-decomposition (trail ?T))
  unfolding all-decomposition-implies-def
proof clarify
  fix a b
  assume (a, b)  $\in$  set (get-all-marked-decomposition (trail ?T))
  from in-get-all-marked-decomposition-in-get-all-marked-decomposition-prepend[OF this]
  obtain b' where
    (a, b' @ b)  $\in$  set (get-all-marked-decomposition (trail T))
    using M by simp metis
  then have ( $\lambda a. \{\#lit\text{-of } a\# \}$ )  $\cup$  set-mset (init-clss ?T)
     $\models_{ps}$  ( $\lambda a. \{\#lit\text{-of } a\# \}$ )  $\cup$  set (b @ b')
    using decomp-T unfolding all-decomposition-implies-def

  apply auto
  by (metis (no-types, lifting) case-prodD set-append sup commute true-clss-clss-insert-l)

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    then show (λa. {#lit-of a#}) ‘ set a ∪ set-mset (init-clss ?T)
      |=ps (λa. {#lit-of a#}) ‘ set b
      by (auto simp: image-Un)
qed

have [simp]: cdclW-learned-clause ?T
  using inv-T unfolding cdclW-all-struct-inv-def cdclW-learned-clause-def
  by (auto dest!: H-proped simp: clauses-def)
show ?thesis
  using (all-decomposition-implies-m (init-clss ?T)
    (get-all-marked-decomposition (trail ?T)))
  unfolding cdclW-all-struct-inv-def by (auto simp: add-new-clause-and-update-def)
qed

lemma cdclW-all-struct-inv-add-new-clause-and-update-cdclW-stgy-inv:
  assumes
    inv-s: cdclW-stgy-invariant T and
    inv: cdclW-all-struct-inv T and
    tr-T-N[simp]: trail T |=asm N and
    tr-C[simp]: trail T |=as CNot C and
    [simp]: distinct-mset C
  shows cdclW-stgy-invariant (add-new-clause-and-update C T) (is cdclW-stgy-invariant ?T')
proof -
  have cdclW-all-struct-inv ?T'
    using cdclW-all-struct-inv-add-new-clause-and-update-cdclW-all-struct-inv assms by blast
  then have
    no-dup-cut-T[simp]: no-dup (trail (cut-trail-wrt-clause C (trail T) T)) and
    n-d[simp]: no-dup (trail T)
    using cdclW-M-level-inv-decomp(2) cdclW-all-struct-inv-def inv
    n-dup-no-dup-trail-cut-trail-wrt-clause by blast+
  then have trail (add-new-clause-and-update C T) |=as CNot C
    by (simp add: add-new-clause-and-update-def cut-trail-wrt-clause-CNot-trail
      cdclW-M-level-inv-def cdclW-all-struct-inv-def)
  obtain MT where
    MT: trail T = MT @ trail (cut-trail-wrt-clause C (trail T) T)
    using trail-cut-trail-wrt-clause by blast
  consider
    (false) ∨ L ∈ #C. – L ∉ lits-of (trail T) and trail (cut-trail-wrt-clause C (trail T) T) = []
    | (not-false) – lit-of (hd (trail (cut-trail-wrt-clause C (trail T) T))) ∈ # C and
      1 ≤ length (trail (cut-trail-wrt-clause C (trail T) T))
    using cut-trail-wrt-clause-hd-trail-in-or-empty-trail[of C T] by auto
  then show ?thesis
  proof cases
    case false note C = this(1) and empty-tr = this(2)
    then have [simp]: C = {#}
      by (simp add: in-CNot-implies-uminus(2) multiset-eqI)
    show ?thesis
      using empty-tr unfolding cdclW-stgy-invariant-def no-smaller-confl-def
      cdclW-all-struct-inv-def by (auto simp: add-new-clause-and-update-def)
  next
    case not-false note C = this(1) and l = this(2)
    let ?L = – lit-of (hd (trail (cut-trail-wrt-clause C (trail T) T)))
    have get-all-levels-of-marked (trail (add-new-clause-and-update C T)) =
      rev [1..<1 + length (get-all-levels-of-marked (trail (add-new-clause-and-update C T)))]

```

```

using  $\langle \text{cdcl}_W\text{-all-struct-inv } ?T' \rangle$  unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$   $\text{cdcl}_W\text{-M-level-inv-def}$ 
by blast
moreover
  have backtrack-lvl (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ ) =
    length (get-all-levels-of-marked (trail (add-new-clause-and-update  $C$   $T$ )))
    using  $\langle \text{cdcl}_W\text{-all-struct-inv } ?T' \rangle$  unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$   $\text{cdcl}_W\text{-M-level-inv-def}$ 
    by (auto simp: add-new-clause-and-update-def)
moreover
  have no-dup (trail (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ ))
    using  $\langle \text{cdcl}_W\text{-all-struct-inv } ?T' \rangle$  unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$   $\text{cdcl}_W\text{-M-level-inv-def}$ 
    by (auto simp: add-new-clause-and-update-def)
  then have atm-of  $?L \notin \text{atm-of } \langle \text{lits-of } (\text{tl } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T))) \rangle$ 
    apply (cases trail (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ ))
    apply (auto)
    using Marked-Propagated-in-iff-in-lits-of defined-lit-map by blast

ultimately have  $L$ : get-level ( $-?L$ ) (trail (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ ))
  = length (get-all-levels-of-marked (trail (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ )))
using get-level-get-rev-level-get-all-levels-of-marked[OF
   $\langle \text{atm-of } ?L \notin \text{atm-of } \langle \text{lits-of } (\text{tl } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T))) \rangle$ ,
  of [hd (trail (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ ))]]
  apply (cases trail (add-init-cls  $C$  (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ ));
  cases hd (trail (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ )))
  using  $l$  by (auto split: split-if-asm
    simp: rev-swap[symmetric] add-new-clause-and-update-def
    simp del:)

have  $L'$ : length (get-all-levels-of-marked (trail (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ )))
  = backtrack-lvl (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ )
  using  $\langle \text{cdcl}_W\text{-all-struct-inv } ?T' \rangle$  unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$   $\text{cdcl}_W\text{-M-level-inv-def}$ 
  by (auto simp: add-new-clause-and-update-def)

have [simp]: no-smaller-confl (update-conflicting ( $C\text{-Clause } C$ )
  (add-init-cls  $C$  (cut-trail-wrt-clause  $C$  (trail  $T$ )  $T$ )))
  unfolding no-smaller-confl-def
proof (clarify, goal-cases)
  case ( $1\ M\ K\ i\ M'\ D$ )
  then consider
    ( $DC$ )  $D = C$ 
    | ( $D-T$ )  $D \in \# \text{clauses } T$ 
  by (auto simp: clauses-def split: split-if-asm)
then show False
  proof cases
    case  $D-T$ 
    have no-smaller-confl  $T$ 
      using inv-s unfolding  $\text{cdcl}_W\text{-stgy-invariant-def}$  by auto
    have ( $MT @ M'$ ) @ Marked  $K\ i\ \# M = \text{trail } T$ 
      using  $MT\ 1(1)$  by auto
    thus False using  $D-T$   $\langle \text{no-smaller-confl } T \rangle\ 1(3)$  unfolding no-smaller-confl-def by blast
  next
    case  $DC$  note  $\neg[\text{simp}] = \text{this}$ 
    then have atm-of ( $-?L$ )  $\in \text{atm-of } \langle \text{lits-of } M \rangle$ 
      using  $1(3)\ C\ \text{in-}C\text{Not-implies-uminus}(2)$  by blast
    moreover

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    have lit-of (hd (M' @ Marked K i # [])) = - ?L
    using l 1(1)[symmetric] inv
    by (cases trail (add-init-cls C (cut-trail-wrt-clause C (trail T) T)))
    (auto dest!: arg-cong[of - # - - hd] simp: hd-append cdclW-all-struct-inv-def
      cdclW-M-level-inv-def)
    from arg-cong[OF this, of atm-of]
    have atm-of (- ?L) ∈ atm-of ' (lits-of (M' @ Marked K i # []))
    by (cases (M' @ Marked K i # [])) auto
    moreover have no-dup (trail (cut-trail-wrt-clause C (trail T) T))
    using ⟨cdclW-all-struct-inv ?T'⟩ unfolding cdclW-all-struct-inv-def
      cdclW-M-level-inv-def by (auto simp: add-new-clause-and-update-def)
    ultimately show False
    unfolding 1(1)[symmetric, simplified]
    apply auto
    using Marked-Propagated-in-iff-in-lits-of defined-lit-map apply blast
    by (metis IntI Marked-Propagated-in-iff-in-lits-of defined-lit-map empty-iff)
  qed
qed
show ?thesis using L L' C
  unfolding cdclW-stgy-invariant-def
  unfolding cdclW-all-struct-inv-def by (auto simp: add-new-clause-and-update-def)
qed
qed

lemma full-cdclW-stgy-inv-normal-form:
  assumes
    full: full cdclW-stgy S T and
    inv-s: cdclW-stgy-invariant S and
    inv: cdclW-all-struct-inv S
  shows conflicting T = C-Clause {#} ∧ unsatisfiable (set-mset (init-clss S))
    ∨ conflicting T = C-True ∧ trail T ⊨asm init-clss S ∧ satisfiable (set-mset (init-clss S))
proof -
  have no-step cdclW-stgy T
  using full unfolding full-def by blast
  moreover have cdclW-all-struct-inv T and inv-s: cdclW-stgy-invariant T
  apply (metis cdclW-ops.rtrancp-cdclW-stgy-rtrancp-cdclW cdclW-ops-axioms full full-def inv
    rtrancp-cdclW-all-struct-inv-inv)
  by (metis full full-def inv inv-s rtrancp-cdclW-stgy-cdclW-stgy-invariant)
  ultimately have conflicting T = C-Clause {#} ∧ unsatisfiable (set-mset (init-clss T))
  ∨ conflicting T = C-True ∧ trail T ⊨asm init-clss T
  using cdclW-stgy-final-state-conclusive[of T] full
  unfolding cdclW-all-struct-inv-def cdclW-stgy-invariant-def full-def by fast
  moreover have consistent-interp (lits-of (trail T))
  using ⟨cdclW-all-struct-inv T⟩ unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def
  by auto
  moreover have init-clss S = init-clss T
  using inv unfolding cdclW-all-struct-inv-def
  by (metis rtrancp-cdclW-stgy-no-more-init-clss full full-def)
  ultimately show ?thesis
  by (metis satisfiable-carac' true-annot-def true-annot-def true-clss-def)
qed

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lemma incremental-cdclW-inv:
  assumes
    inc: incremental-cdclW S T and

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  inv: cdclW-all-struct-inv S and
  s-inv: cdclW-stgy-invariant S
shows
  cdclW-all-struct-inv T and
  cdclW-stgy-invariant T
using inc
proof (induction)
  case (add-conf C T)
  let ?T = (update-conflicting (C-Clause C) (add-init-cls C (cut-trail-wrt-clause C (trail S) S)))
  have cdclW-all-struct-inv ?T and inv-s-T: cdclW-stgy-invariant ?T
    using add-conf.hyps(1,2,4) add-new-clause-and-update-def
    cdclW-all-struct-inv-add-new-clause-and-update-cdclW-all-struct-inv inv apply auto[1]
    using add-conf.hyps(1,2,4) add-new-clause-and-update-def
    cdclW-all-struct-inv-add-new-clause-and-update-cdclW-stgy-inv inv s-inv by auto
  case 1 show ?case
    by (metis add-conf.hyps(1,2,4,5) add-new-clause-and-update-def
        cdclW-all-struct-inv-add-new-clause-and-update-cdclW-all-struct-inv
        rtranclp-cdclW-all-struct-inv-inv rtranclp-cdclW-stgy-rtranclp-cdclW full-def inv)

  case 2 show ?case
    by (metis inv-s-T add-conf.hyps(1,2,4,5) add-new-clause-and-update-def
        cdclW-all-struct-inv-add-new-clause-and-update-cdclW-all-struct-inv full-def inv
        rtranclp-cdclW-stgy-cdclW-stgy-invariant)
next
  case (add-no-conf C T)
  case 1
  have cdclW-all-struct-inv (add-init-cls C S)
    using inv <distinct-mset C> unfolding cdclW-all-struct-inv-def no-strange-atm-def
    cdclW-M-level-inv-def distinct-cdclW-state-def cdclW-conflicting-def cdclW-learned-clause-def
    by (auto simp: all-decomposition-implies-insert-single clauses-def)
  then show ?case
    using add-no-conf(5) unfolding full-def by (auto intro: rtranclp-cdclW-stgy-cdclW-all-struct-inv)
  case 2 have cdclW-stgy-invariant (add-init-cls C S)
    using s-inv <¬ trail S ⊨as CNot C> inv unfolding cdclW-stgy-invariant-def no-smaller-conf-def
    eq-commute[of - trail -] cdclW-M-level-inv-def cdclW-all-struct-inv-def
    by (auto simp: true-annots-true-clauses-def-iff-negation-in-model clauses-def split: split-if-asm)
  then show ?case
    by (metis <cdclW-all-struct-inv (add-init-cls C S)> add-no-conf.hyps(5) full-def
        rtranclp-cdclW-stgy-cdclW-stgy-invariant)
qed

```

lemma *rtranclp-incremental-cdcl_W-inv:*

```

assumes
  inc: incremental-cdclW** S T and
  inv: cdclW-all-struct-inv S and
  s-inv: cdclW-stgy-invariant S
shows
  cdclW-all-struct-inv T and
  cdclW-stgy-invariant T
  using inc apply induction
  using inv apply simp
  using s-inv apply simp
  using incremental-cdclW-inv by blast+

```

lemma *incremental-conclusive-state:*

assumes
inc: *incremental-cdcl_W S T* **and**
inv: *cdcl_W-all-struct-inv S* **and**
s-inv: *cdcl_W-stgy-invariant S*
shows *conflicting T = C-Clause {#} \wedge unsatisfiable (set-mset (init-clss T))*
 \vee *conflicting T = C-True \wedge trail T \models_{asm} init-clss T \wedge satisfiable (set-mset (init-clss T))*
using *inc* **apply** *induction*

apply (*metis Nitpick.rtranclp-unfold add-confl full-cdcl_W-stgy-inv-normal-form full-def*
incremental-cdcl_W-inv(1) incremental-cdcl_W-inv(2) inv s-inv)
by (*metis (full-types) rtranclp-unfold add-no-confl full-cdcl_W-stgy-inv-normal-form*
full-def incremental-cdcl_W-inv(1) incremental-cdcl_W-inv(2) inv s-inv)

lemma *tranclp-incremental-correct*:

assumes
inc: *incremental-cdcl_W⁺⁺ S T* **and**
inv: *cdcl_W-all-struct-inv S* **and**
s-inv: *cdcl_W-stgy-invariant S*
shows *conflicting T = C-Clause {#} \wedge unsatisfiable (set-mset (init-clss T))*
 \vee *conflicting T = C-True \wedge trail T \models_{asm} init-clss T \wedge satisfiable (set-mset (init-clss T))*
using *inc* **apply** *induction*
using *assms incremental-conclusive-state* **apply** *blast*
by (*meson incremental-conclusive-state inv rtranclp-incremental-cdcl_W-inv s-inv*
tranclp-into-rtranclp)

lemma *blocked-induction-with-marked*:

assumes
n-d: *no-dup (L # M)* **and**
nil: *P []* **and**
append: $\bigwedge M L M'. P M \implies is_marked L \implies \forall m \in set M'. \neg is_marked m \implies no_dup (L \# M' @ M) \implies$
 $P (L \# M' @ M)$ **and**
L: *is-marked L*
shows
P (L # M)
using *n-d L*
proof (*induction card {L' \in set M. is-marked L'}* *arbitrary: L M*)
case 0 **note** *n = this(1)* **and** *n-d = this(2)* **and** *L = this(3)*
then have $\forall m \in set M. \neg is_marked m$ **by** *auto*
then show ?case **using** *append[of [] L M]* *L nil n-d* **by** *auto*
next
case (*Suc n*) **note** *IH = this(1)* **and** *n = this(2)* **and** *n-d = this(3)* **and** *L = this(4)*
have $\exists L' \in set M. is_marked L'$
proof (*rule ccontr*)
assume $\neg ?thesis$
then have *H*: $\{L' \in set M. is_marked L'\} = \{\}$
by *auto*
show *False* **using** *n* **unfolding** *H* **by** *auto*
qed
then obtain *L' M' M''* **where**
M: *M = M' @ L' # M''* **and**
L': *is-marked L'* **and**
nm: $\forall m \in set M'. \neg is_marked m$
by (*auto elim!: split-list-first-propE*)
have *Suc n = card {L' \in set M. is-marked L'}*

using n .
 moreover have $\{L' \in \text{set } M. \text{ is-marked } L'\} = \{L'\} \cup \{L' \in \text{set } M''. \text{ is-marked } L'\}$
 using $nm \ L' \ n\text{-d} \text{ unfolding } M \text{ by auto}$
 moreover have $L' \notin \{L' \in \text{set } M''. \text{ is-marked } L'\}$
 using $n\text{-d} \text{ unfolding } M \text{ by auto}$
 ultimately have $n = \text{card } \{L'' \in \text{set } M''. \text{ is-marked } L''\}$
 using $n \ L' \text{ by auto}$
 then have $P \ (L' \# M'')$ using $IH \ L' \ n\text{-d} \ M \text{ by auto}$
 then show ?case using $\text{append}[of \ L' \# M'' \ L \ M'] \ nm \ L \ n\text{-d} \text{ unfolding } M \text{ by blast}$
 qed

lemma *trail-bloc-induction*:

assumes
 $n\text{-d}$: $\text{no-dup } M$ and
 nil : $P \ []$ and
 append : $\bigwedge M \ L \ M'. \ P \ M \implies \text{is-marked } L \implies \forall m \in \text{set } M'. \neg \text{is-marked } m \implies \text{no-dup } (L \# M' @ M) \implies$
 $P \ (L \# M' @ M)$ and
 append-nm : $\bigwedge M' \ M''. \ P \ M' \implies M = M'' @ M' \implies \forall m \in \text{set } M''. \neg \text{is-marked } m \implies P \ M$
 shows
 $P \ M$
proof (cases $\{L' \in \text{set } M. \text{ is-marked } L'\} = \{\}$)
 case *True*
 then show ?thesis using $\text{append-nm}[of \ [] \ M] \ nil \text{ by auto}$
 next
 case *False*
 then have $\exists L' \in \text{set } M. \text{ is-marked } L'$
 by auto
 then obtain $L' \ M' \ M''$ where
 M : $M = M' @ L' \# M''$ and
 L' : $\text{is-marked } L'$ and
 nm : $\forall m \in \text{set } M'. \neg \text{is-marked } m$
 by (auto elim!: *split-list-first-propE*)
 have $P \ (L' \# M'')$
 apply (rule *blocked-induction-with-marked*)
 using $n\text{-d} \text{ unfolding } M \text{ apply simp}$
 using $nil \text{ apply simp}$
 using $\text{append} \text{ apply simp}$
 using $L' \text{ by auto}$
 then show ?thesis
 using $\text{append-nm}[of \ - \ M'] \ nm \text{ unfolding } M \text{ by simp}$
 qed

inductive *Tcons* :: $('v, \text{nat}, 'v \text{ clause}) \text{ marked-lits} \Rightarrow ('v, \text{nat}, 'v \text{ clause}) \text{ marked-lits} \Rightarrow \text{bool}$
for $M :: ('v, \text{nat}, 'v \text{ clause}) \text{ marked-lits}$ **where**
 $Tcons \ M \ [] \mid$
 $Tcons \ M \ M' \implies M = M'' @ M' \implies (\forall m \in \text{set } M''. \neg \text{is-marked } m) \implies Tcons \ M \ (M'' @ M') \mid$
 $Tcons \ M \ M' \implies \text{is-marked } L \implies M = M''' @ L \# M'' @ M' \implies (\forall m \in \text{set } M''. \neg \text{is-marked } m) \implies$
 $Tcons \ M \ (L \# M'' @ M')$

lemma *Tcons-same-end*: $Tcons \ M \ M' \implies \exists M''. M = M'' @ M'$
 by (induction rule: *Tcons.induct*) auto

end

end

theory *CDCL-Two-Watched-Literals*
imports *CDCL-WNOT*
begin

Only the 2-watched literals have to be verified here: the backtrack level and the trail can remain separate.

datatype *'v twl-clause* =
TWL-Clause (*watched: 'v clause*) (*unwatched: 'v clause*)

abbreviation *raw-clause* :: *'v twl-clause* \Rightarrow *'v clause* **where**
raw-clause *C* \equiv *watched C* + *unwatched C*

datatype (*'v, 'lvl, 'mark*) *twl-state* =
TWL-State (*trail: ('v, 'lvl, 'mark) marked-lits*) (*init-clss: 'v twl-clause multiset*)
(*learned-clss: 'v twl-clause multiset*) (*backtrack-lvl: 'lvl*)
(*conflicting: 'v clause conflicting-clause*)

abbreviation *raw-init-clss* **where**
raw-init-clss *S* \equiv *image-mset raw-clause (init-clss S)*

abbreviation *raw-learned-clsss* **where**
raw-learned-clsss *S* \equiv *image-mset raw-clause (learned-clss S)*

abbreviation *clauses* **where**
clauses *S* \equiv *init-clss S* + *learned-clss S*

definition
candidates-propagate :: (*'v, 'lvl, 'mark*) *twl-state* \Rightarrow (*'v literal* \times *'v clause*) *set*
where
candidates-propagate *S* =
 $\{(L, \text{raw-clause } C) \mid L \in \# \text{ clauses } S \wedge \text{watched } C - \text{mset-set } (\text{uminus ' lits-of } (\text{trail } S)) = \{\#L\# \} \wedge \text{undefined-lit } (\text{trail } S) L\}$

definition *candidates-conflict* :: (*'v, 'lvl, 'mark*) *twl-state* \Rightarrow *'v clause set* **where**
candidates-conflict *S* =
 $\{\text{raw-clause } C \mid C. C \in \# \text{ clauses } S \wedge \text{watched } C \subseteq \# \text{ mset-set } (\text{uminus ' lits-of } (\text{trail } S))\}$

primrec (*nonexhaustive*) *index* :: *'a list* \Rightarrow *'a* \Rightarrow *nat* **where**
index (*a # l*) *c* = (if *a* = *c* then 0 else 1 + *index l c*)

lemma *index-nth*:
 $a \in \text{set } l \implies l ! (\text{index } l a) = a$
by (*induction l*) *auto*

We need the following property: if there is a literal *L* with $-L$ in the trail and *L* is not watched, then it stays unwatched; i.e., while updating with *rewatch* it does not get swap with a watched literal *L'* such that $-L'$ is in the trail.

primrec *watched-decided-most-recently* :: (*'v, 'lvl, 'mark*) *marked-lit list* \Rightarrow *'v twl-clause* \Rightarrow *bool*
where
watched-decided-most-recently *M* (*TWL-Clause W UW*) \longleftrightarrow
 $(\forall L' \in \# W. \forall L \in \# UW. \text{undefined-lit } (\text{trail } S) L)$

$-L' \in \text{lits-of } M \longrightarrow -L \in \text{lits-of } M \longrightarrow$
 $\text{index } (\text{map lit-of } M) (-L') \leq \text{index } (\text{map lit-of } M) (-L)$

primrec $\text{wf-twl-cl}\text{::} ('v, 'wl, 'mark) \text{ marked-lit list} \Rightarrow 'v \text{ twl-clause} \Rightarrow \text{bool}$ **where**
 $\text{wf-twl-cl}\text{ } M \text{ (TWL-Clause } W \text{ UW)} \longleftrightarrow$
 $\text{distinct-mset } W \wedge \text{size } W \leq 2 \wedge (\text{size } W < 2 \longrightarrow \text{set-mset } UW \subseteq \text{set-mset } W) \wedge$
 $(\forall L \in \# W. -L \in \text{lits-of } M \longrightarrow (\forall L' \in \# UW. L' \notin \# W \longrightarrow -L' \in \text{lits-of } M)) \wedge$
 $\text{watched-decided-most-recently } M \text{ (TWL-Clause } W \text{ UW)}$

lemma $-L \in \text{lits-of } M \implies \{i. \text{map lit-of } M!i = -L\} \neq \{\}$
unfolding $\text{set-map-lit-of-lits-of[symmetric]} \text{ set-conv-nth}$
by $(\text{smt Collect-empty-eq mem-Collect-eq})$

lemma $\text{size-mset-2: size } x1 = 2 \longleftrightarrow (\exists a \text{ b. } x1 = \{\#a, \#b\})$
by $(\text{metis (no-types, hide-lams) Suc-eq-plus1 one-add-one size-1-singleton-mset}$
 $\text{size-Diff-singleton size-Suc-Diff1 size-eq-Suc-imp-eq-union size-single union-single-eq-diff}$
 $\text{union-single-eq-member})$

lemma $\text{distinct-mset-size-2: distinct-mset } \{\#a, \#b\} \longleftrightarrow a \neq b$
unfolding distinct-mset-def **by** auto

does not hold when all there are multiple conflicts in a clause.

lemma $\text{wf-twl-cl}\text{wf-twl-cl}\text{-tl:}$

assumes $\text{wf: wf-twl-cl}\text{ } M \text{ } C$ **and** $n\text{-d: no-dup } M$

shows $\text{wf-twl-cl}\text{ (tl } M) \text{ } C$

proof $(\text{cases } M)$

case Nil

then show $?thesis$ **using** wf

by $(\text{cases } C) (\text{simp add: wf-twl-cl.simps[of tl -]})$

next

case $(\text{Cons } l \text{ } M')$ **note** $M = \text{this}(1)$

obtain $W \text{ UW}$ **where** $C: C = \text{TWL-Clause } W \text{ UW}$

by $(\text{cases } C)$

{ fix $L \text{ } L'$

assume

$LW: L \in \# W$ **and**

$LM: -L \in \text{lits-of } M'$ **and**

$L'UW: L' \in \# UW$ **and**

$\text{count } W \text{ } L' = 0$

then have

$L'M: -L' \in \text{lits-of } M$

using wf **by** $(\text{auto simp: } C \text{ } M)$

have $\text{watched-decided-most-recently } M \text{ } C$

using wf **by** $(\text{auto simp: } C)$

then have

$\text{index } (\text{map lit-of } M) (-L) \leq \text{index } (\text{map lit-of } M) (-L')$

using $LM \text{ } L'M \text{ } L'UW \text{ } LW$ **by** $(\text{metis (mono-tags, lifting) } C \text{ } M \text{ bspec-mset insert-iff lits-of-cons}$
 $\text{watched-decided-most-recently.simps})$

then have $-L' \in \text{lits-of } M'$

using $\langle \text{count } W \text{ } L' = 0 \rangle \text{ } LW \text{ } L'M$ **by** $(\text{auto simp: } C \text{ } M \text{ split: split-if-asm})$

}

moreover

{

fix $L \text{ } L' \text{ } La$

assume

```

     $L \in \# W$  and
     $LM': - L \in \text{ lits-of } M'$  and
     $L' \in \# W$  and
     $La \in \# UW$  and
     $L'M: - L' \in \text{ lits-of } M'$  and
     $- La \in \text{ lits-of } M'$ 
  moreover
    have  $\text{lit-of } l \neq - L'$ 
    using  $n\text{-d}$ 
      by (metis (no-types)  $L'M$   $M$  Marked-Propagated-in-iff-in-lits-of defined-lit-map
        distinct.simps(2) list.simps(9) set-map)
    moreover have watched-decided-most-recently  $M$   $C$ 
      using wf by (auto simp:  $C$ )
    ultimately have  $\text{index } (\text{map lit-of } M') (- L') \leq \text{index } (\text{map lit-of } M') (- La)$ 
      by (auto simp:  $M$   $C$  split: split-if-asm)
  }
  moreover have distinct-mset  $W$  and  $\text{size } W \leq 2$  and  $(\text{size } W < 2 \longrightarrow \text{set-mset } UW \subseteq \text{set-mset } W)$ 
    using wf by (auto simp:  $C$   $M$ )
  ultimately show ?thesis by (simp add:  $M$   $C$ )
qed

```

definition $\text{wf-twl-state} :: ('v, 'wl, 'mark) \text{ twl-state} \Rightarrow \text{bool}$ **where**
 $\text{wf-twl-state } S \longleftrightarrow (\forall C \in \# \text{ clauses } S. \text{ wf-twl-cl } (\text{trail } S) C) \wedge \text{no-dup } (\text{trail } S)$

lemma $\text{wf-candidates-propagate-sound}$:

```

  assumes wf:  $\text{wf-twl-state } S$  and
    cand:  $(L, C) \in \text{candidates-propagate } S$ 
  shows  $\text{trail } S \models_{\text{as}} C \text{Not } (\text{mset-set } (\text{set-mset } C - \{L\})) \wedge \text{undefined-lit } (\text{trail } S) L$ 

```

proof

```

  def  $M \equiv \text{trail } S$ 
  def  $N \equiv \text{init-clss } S$ 
  def  $U \equiv \text{learned-clss } S$ 

```

note $MNU\text{-defs } [\text{simp}] = M\text{-def } N\text{-def } U\text{-def}$

obtain Cw **where** cw :

```

   $C = \text{raw-clause } Cw$ 
   $Cw \in \# N + U$ 
   $\text{watched } Cw - \text{mset-set } (\text{uminus } ' \text{ lits-of } M) = \{\#L\# \}$ 
   $\text{undefined-lit } M L$ 
  using cand unfolding  $\text{candidates-propagate-def } MNU\text{-defs}$  by blast

```

obtain W UW **where** $cw\text{-eq}: Cw = \text{TWL-Clause } W$ UW

by (case-tac Cw , blast)

have $l\text{-w}: L \in \# W$

by (metis Multiset.diff-le-self $cw(3)$ $cw\text{-eq}$ mset-leD multi-member-last $\text{twl-clause.sel}(1)$)

have $\text{wf-c}: \text{wf-twl-cl } M$ Cw

using wf $(Cw \in \# N + U)$ **unfolding** wf-twl-state-def **by** simp

have $w\text{-nw}$:

```

  distinct-mset  $W$ 
   $\text{size } W < 2 \implies \text{set-mset } UW \subseteq \text{set-mset } W$ 

```

$\bigwedge L L'. L \in \# W \implies -L \in \text{lots-of } M \implies L' \in \# UW \implies L' \notin \# W \implies -L' \in \text{lots-of } M$
using *wf-c* **unfolding** *cw-eq* **by** *auto*

have $\forall L' \in \text{set-mset } C - \{L\}. -L' \in \text{lots-of } M$
proof (*cases size W < 2*)
 case *True*
 moreover have *size W ≠ 0*
 using *cw(3) cw-eq* **by** *auto*
 ultimately have *size W = 1*
 by *linarith*
 then have *w: W = {#L#}*
 by (*metis (no-types, lifting) Multiset.diff-le-self cw(3) cw-eq single-not-empty size-1-singleton-mset subset-mset.add-diff-inverse union-is-single twl-clause.sel(1)*)
 from *True* **have** *set-mset UW ⊆ set-mset W*
 using *w-nw(2)* **by** *blast*
 then show *?thesis*
 using *w cw(1) cw-eq* **by** *auto*
next
 case *sz2: False*
 show *?thesis*
 proof
 fix *L'*
 assume *l': L' ∈ set-mset C - {L}*
 have *ex-la: ∃ La. La ≠ L ∧ La ∈ # W*
 proof (*cases W*)
 case *empty*
 thus *?thesis*
 using *l-w* **by** *auto*
 next
 case *lb: (add W' Lb)*
 show *?thesis*
 proof (*cases W'*)
 case *empty*
 thus *?thesis*
 using *lb sz2* **by** *simp*
 next
 case *lc: (add W'' Lc)*
 thus *?thesis*
 by (*metis add-gr-0 count-union distinct-mset-single-add lb union-single-eq-member w-nw(1)*)
 qed
 qed
 then obtain *La* **where** *la: La ≠ L La ∈ # W*
 by *blast*
 then have *La ∈ # mset-set (uminus ' lots-of M)*
 using *cw(3)[unfolded cw-eq, simplified, folded M-def]*
 by (*metis count-diff count-single diff-zero not-gr0*)
 then have *nla: -La ∈ lots-of M*
 by *auto*
 then show $-L' \in \text{lots-of } M$

proof –
 have *f1: L' ∈ set-mset C*
 using *l'* **by** *blast*
 have *f2: L' ∉ {L}*

```

    using l' by fastforce
  have  $\bigwedge l. - (l::'a \text{ literal}) \in L \vee l \notin \text{uminus } 'L$ 
    by force
  then have  $\bigwedge l. - l \in \text{lits-of } M \vee \text{count } \{\#L\} \ l = \text{count } (C - UW) \ l$ 
    by (metis (no-types) add-diff-cancel-right' count-diff count-mset-set(3) cw(1) cw(3)
      cw-eq diff-zero twl-clause.sel(2))
  then show ?thesis
    by (smt comm-monoid-add-class.add-0 cw(1) cw-eq diff-union-cancelR ex-la f1 f2 insertCI
      less-numeral-extra(3) mem-set-mset-iff plus-multiset.rep-eq single.rep-eq
      twl-clause.sel(1) twl-clause.sel(2) w-nw(3))
qed
qed
qed
then show  $\text{trail } S \models_{\text{as}} \text{CNot } (\text{mset-set } (\text{set-mset } C - \{L\}))$ 
  unfolding true-annots-def by auto

show undefined-lit (trail S) L
  using cw(4) M-def by blast
qed

```

lemma *wf-candidates-propagate-complete:*

```

assumes wf: wf-twL-state S and
  c-mem:  $C \in \# \text{ image-mset raw-clause } (\text{clauses } S)$  and
  l-mem:  $L \in \# C$  and
  unsat:  $\text{trail } S \models_{\text{as}} \text{CNot } (\text{mset-set } (\text{set-mset } C - \{L\}))$  and
  undef: undefined-lit (trail S) L
shows  $(L, C) \in \text{candidates-propagate } S$ 
proof -
  def M  $\equiv \text{trail } S$ 
  def N  $\equiv \text{init-clss } S$ 
  def U  $\equiv \text{learned-clss } S$ 

```

note $\text{MNU-defs } [\text{simp}] = \text{M-def } \text{N-def } \text{U-def}$

obtain Cw **where** cw: $C = \text{raw-clause } Cw$ $Cw \in \# N + U$
 using c-mem by force

obtain W UW **where** cw-eq: $Cw = \text{TWL-Clause } W \ UW$
 by (case-tac Cw, blast)

have wf-c: wf-twL-clS M Cw
 using wf cw(2) unfolding wf-twL-state-def by simp

have w-nw:
 distinct-mset W
 size W < 2 $\implies \text{set-mset } UW \subseteq \text{set-mset } W$
 $\bigwedge L \ L'. L \in \# W \implies -L \in \text{lits-of } M \implies L' \in \# UW \implies L' \notin \# W \implies -L' \in \text{lits-of } M$
 using wf-c unfolding cw-eq by auto

have unit-set: $\text{set-mset } (W - \text{mset-set } (\text{uminus } ' \text{lits-of } M)) = \{L\}$

proof

show $\text{set-mset } (W - \text{mset-set } (\text{uminus } ' \text{lits-of } M)) \subseteq \{L\}$

proof

fix L'

assume l': $L' \in \text{set-mset } (W - \text{mset-set } (\text{uminus } ' \text{lits-of } M))$

```

hence  $l'$ -mem-w:  $L' \in \text{set-mset } W$ 
  by auto
have  $L' \notin \text{uminus ' lits-of } M$ 
  using distinct-mem-diff-mset[OF w-nw(1) l'] by simp
then have  $\neg M \models_a \{\# - L'\#\}$ 
  using image-iff by fastforce
moreover have  $L' \in \# C$ 
  using cw(1) cw-eq l'-mem-w by auto
ultimately have  $L' = L$ 
  unfolding M-def by (metis unsat[unfolded CNot-def true-annots-def, simplified])
then show  $L' \in \{L\}$ 
  by simp
qed
next
show  $\{L\} \subseteq \text{set-mset } (W - \text{mset-set } (\text{uminus ' lits-of } M))$ 
proof clarify
  have  $L \in \# W$ 
  proof (cases W)
    case empty
    thus ?thesis
    using w-nw(2) cw(1) cw-eq l-mem by auto
  next
    case (add W' La)
    thus ?thesis
    proof (cases La = L)
      case True
      thus ?thesis
      using add by simp
    next
      case False
      have  $-La \in \text{lits-of } M$ 
      using False add cw(1) cw-eq unsat[unfolded CNot-def true-annots-def, simplified]
      by fastforce
      then show ?thesis
      by (metis M-def Marked-Propagated-in-iff-in-lits-of add add.left-neutral count-union
        cw(1) cw-eq grOI l-mem twl-clause.sel(1) twl-clause.sel(2) undef union-single-eq-member
        w-nw(3))
    qed
  qed
moreover have  $L \notin \# \text{mset-set } (\text{uminus ' lits-of } M)$ 
  using Marked-Propagated-in-iff-in-lits-of undef by auto
ultimately show  $L \in \text{set-mset } (W - \text{mset-set } (\text{uminus ' lits-of } M))$ 
  by auto
qed
qed
have unit:  $W - \text{mset-set } (\text{uminus ' lits-of } M) = \{\#L\#\}$ 
  by (metis distinct-mset-minus distinct-mset-set-mset-ident distinct-mset-singleton
    set-mset-single unit-set w-nw(1))

show ?thesis
  unfolding candidates-propagate-def using unit undef cw cw-eq by fastforce
qed

lemma wf-candidates-conflict-sound:
  assumes wf: wf-twl-state S and

```



```

  cand:  $C \in \text{candidates-conflict } S$ 
shows  $\text{trail } S \models_{\text{as}} C \text{Not } C \wedge C \in \# \text{ image-mset raw-clause } (\text{clauses } S)$ 
proof
  def  $M \equiv \text{trail } S$ 
  def  $N \equiv \text{init-clss } S$ 
  def  $U \equiv \text{learned-clss } S$ 

  note  $MNU\text{-defs } [\text{simp}] = M\text{-def } N\text{-def } U\text{-def}$ 

  obtain  $Cw$  where  $cw$ :
     $C = \text{raw-clause } Cw$ 
     $Cw \in \# N + U$ 
     $\text{watched } Cw \subseteq \# \text{ mset-set } (\text{uminus ' lits-of } (\text{trail } S))$ 
    using  $\text{cand}[\text{unfolded candidates-conflict-def, simplified}]$  by  $\text{auto}$ 

  obtain  $W UW$  where  $cw\text{-eq}: Cw = \text{TWL-Clause } W UW$ 
    by  $(\text{case-tac } Cw, \text{blast})$ 

  have  $wf\text{-c}: wf\text{-twl-clss } M Cw$ 
    using  $wf\text{ } cw(2)$  unfolding  $wf\text{-twl-state-def}$  by  $\text{simp}$ 

  have  $w\text{-nw}$ :
     $\text{distinct-mset } W$ 
     $\text{size } W < 2 \implies \text{set-mset } UW \subseteq \text{set-mset } W$ 
     $\bigwedge L L'. L \in \# W \implies -L \in \text{lits-of } M \implies L' \in \# UW \implies L' \notin \# W \implies -L' \in \text{lits-of } M$ 
    using  $wf\text{-c}$  unfolding  $cw\text{-eq}$  by  $\text{auto}$ 

  have  $\forall L \in \# C. -L \in \text{lits-of } M$ 
  proof  $(\text{cases } W = \{\#\})$ 
    case  $\text{True}$ 
    then have  $C = \{\#\}$ 
    using  $cw(1) \text{ } cw\text{-eq } w\text{-nw}(2)$  by  $\text{auto}$ 
    then show  $?thesis$ 
    by  $\text{simp}$ 
  next
    case  $\text{False}$ 
    then obtain  $La$  where  $la: La \in \# W$ 
    using  $\text{multiset-eq-iff}$  by  $\text{force}$ 
    show  $?thesis$ 
    proof
    fix  $L$ 
    assume  $l: L \in \# C$ 
    show  $-L \in \text{lits-of } M$ 
    proof  $(\text{cases } L \in \# W)$ 
    case  $\text{True}$ 
    thus  $?thesis$ 
    using  $cw(3) \text{ } cw\text{-eq}$  by  $\text{fastforce}$ 
    next
    case  $\text{False}$ 
    thus  $?thesis$ 
    by  $(\text{smt } M\text{-def } l \text{ add-diff-cancel-left' count-diff } cw(1) \text{ } cw(3) \text{ } la \text{ } cw\text{-eq}$ 
       $\text{diff-zero elem-mset-set finite-imageI finite-lits-of-def grOI imageE mset-leD}$ 
       $\text{uminus-of-uminus-id twl-clause.sel(1) twl-clause.sel(2) } w\text{-nw}(3))$ 
    qed
  qed

```

```

qed
then show  $trail\ S \models_{as} CNot\ C$ 
  unfolding  $CNot-def\ true-annots-def$  by auto

show  $C \in \# image-mset\ raw-clause\ (clauses\ S)$ 
  using  $cw$  by auto
qed

lemma wf-candidates-conflict-complete:
  assumes  $wf: wf-twl-state\ S$  and
     $c-mem: C \in \# image-mset\ raw-clause\ (clauses\ S)$  and
     $unsat: trail\ S \models_{as} CNot\ C$ 
  shows  $C \in candidates-conflict\ S$ 
proof -
  def  $M \equiv trail\ S$ 
  def  $N \equiv init-clss\ S$ 
  def  $U \equiv learned-clss\ S$ 

  note  $MNU-defs\ [simp] = M-def\ N-def\ U-def$ 

  obtain  $Cw$  where  $cw: C = raw-clause\ Cw\ Cw \in \# N + U$ 
    using  $c-mem$  by force

  obtain  $W\ UW$  where  $cw-eq: Cw = TWL-Clause\ W\ UW$ 
    by (case-tac  $Cw$ , blast)

  have  $wf-c: wf-twl-clss\ M\ Cw$ 
    using  $wf\ cw(2)$  unfolding  $wf-twl-state-def$  by simp

  have  $w-nw$ :
     $distinct-mset\ W$ 
     $size\ W < 2 \implies set-mset\ UW \subseteq set-mset\ W$ 
     $\bigwedge L\ L'. L \in \# W \implies -L \in lits-of\ M \implies L' \in \# UW \implies L' \notin \# W \implies -L' \in lits-of\ M$ 
    using  $wf-c$  unfolding  $cw-eq$  by auto

  have  $\bigwedge L. L \in \# C \implies -L \in lits-of\ M$ 
    unfolding  $M-def$  using  $unsat[unfolded\ CNot-def\ true-annots-def, simplified]$  by blast
  then have  $set-mset\ C \subseteq uminus\ 'lits-of\ M$ 
    by (metis  $imageI\ mem-set-mset-iff\ subsetI\ uminus-of-uminus-id$ )
  then have  $set-mset\ W \subseteq uminus\ 'lits-of\ M$ 
    using  $cw(1)\ cw-eq$  by auto
  then have  $subset: W \subseteq \# mset-set\ (uminus\ 'lits-of\ M)$ 
    by (simp add:  $w-nw(1)$ )

  have  $W = watched\ Cw$ 
    using  $cw-eq\ twl-clause.sel(1)$  by simp
  then show ?thesis
    using  $MNU-defs\ cw(1)\ cw(2)\ subset\ candidates-conflict-def$  by blast
qed

typedef  $'v\ wf-twl = \{S::('v, nat, 'v\ clause)\ twl-state.\ wf-twl-state\ S\}$ 
morphisms rough-state-of-twl twl-of-rough-state
proof -
  have  $TWL-State\ ([::('v, nat, 'v\ clause)\ marked-lits)$ 
     $\{\#\}\ \{\#\}\ 0\ C-True \in \{S::('v, nat, 'v\ clause)\ twl-state.\ wf-twl-state\ S\}$ 

```

by (auto simp: wf-twl-state-def)
 then show ?thesis by auto
 qed

lemma *wf-twl-state-rough-state-of-twl*[simp]: *wf-twl-state* (*rough-state-of-twl* *S*)
 using *rough-state-of-twl* by auto

abbreviation *candidates-conflict-twl* :: '*v* *wf-twl* \Rightarrow '*v* literal multiset set **where**
candidates-conflict-twl *S* \equiv *candidates-conflict* (*rough-state-of-twl* *S*)

abbreviation *candidates-propagate-twl* :: '*v* *wf-twl* \Rightarrow ('*v* literal \times '*v* clause) set **where**
candidates-propagate-twl *S* \equiv *candidates-propagate* (*rough-state-of-twl* *S*)

abbreviation *trail-twl* :: '*a* *wf-twl* \Rightarrow ('*a*, nat, '*a* literal multiset) marked-lit list **where**
trail-twl *S* \equiv *trail* (*rough-state-of-twl* *S*)

abbreviation *clauses-twl* :: '*a* *wf-twl* \Rightarrow '*a* twl-clause multiset **where**
clauses-twl *S* \equiv *clauses* (*rough-state-of-twl* *S*)

abbreviation *init-clss-twl* **where**
init-clss-twl *S* \equiv *image-mset* *raw-clause* (*init-clss* (*rough-state-of-twl* *S*))

abbreviation *learned-clss-twl* **where**
learned-clss-twl *S* \equiv *image-mset* *raw-clause* (*learned-clss* (*rough-state-of-twl* *S*))

abbreviation *backtrack-lvl-twl* **where**
backtrack-lvl-twl *S* \equiv *backtrack-lvl* (*rough-state-of-twl* *S*)

abbreviation *conflicting-twl* **where**
conflicting-twl *S* \equiv *conflicting* (*rough-state-of-twl* *S*)

locale *abstract-twl* =

fixes

watch :: ('*v*, nat, '*v* clause) *twl-state* \Rightarrow '*v* clause \Rightarrow '*v* twl-clause **and**
rewatch :: ('*v*, nat, '*v* literal multiset) marked-lit \Rightarrow ('*v*, nat, '*v* clause) *twl-state* \Rightarrow
 '*v* twl-clause \Rightarrow '*v* twl-clause **and**
linearize :: '*v* clauses \Rightarrow '*v* clause list **and**
restart-learned :: ('*v*, nat, '*v* clause) *twl-state* \Rightarrow '*v* twl-clause multiset

assumes

clause-watch: *no-dup*(*trail* *S*) \implies *raw-clause* (*watch* *S* *C*) = *C* **and**
wf-watch: *no-dup* (*trail* *S*) \implies *wf-twl-cls* (*trail* *S*) (*watch* *S* *C*) **and**
clause-rewatch: *raw-clause* (*rewatch* *L* *S* *C'*) = *raw-clause* *C'* **and**
wf-rewatch: *wf-twl-cls* (*trail* *S*) *C'* \implies *wf-twl-cls* (*L* # *trail* *S*) (*rewatch* *L* *S* *C'*) **and**
linearize: *mset* (*linearize* *N*) = *N* **and**
restart-learned: *restart-learned* *S* \subseteq # *learned-clss* *S*

begin

lemma *linearize-mempty*[simp]: *linearize* {#} = []
 using *linearize* *mset-zero-iff* by blast

definition

cons-trail :: ('*v*, nat, '*v* clause) marked-lit \Rightarrow ('*v*, nat, '*v* clause) *twl-state* \Rightarrow
 ('*v*, nat, '*v* clause) *twl-state*

where

cons-trail *L* *S* =

$TWL\text{-}State\ (L\ \# \ trail\ S)\ (image\text{-}mset\ (rewatch\ L\ S)\ (init\text{-}clss\ S))$
 $(image\text{-}mset\ (rewatch\ L\ S)\ (learned\text{-}clss\ S))\ (backtrack\text{-}lvl\ S)\ (conflicting\ S)$

definition

$add\text{-}init\text{-}cls :: 'v\ clause \Rightarrow ('v, nat, 'v\ clause)\ twl\text{-}state \Rightarrow$
 $('v, nat, 'v\ clause)\ twl\text{-}state$

where

$add\text{-}init\text{-}cls\ C\ S =$
 $TWL\text{-}State\ (trail\ S)\ (\{\#watch\ S\ C\#\} + init\text{-}clss\ S)\ (learned\text{-}clss\ S)\ (backtrack\text{-}lvl\ S)$
 $(conflicting\ S)$

definition

$add\text{-}learned\text{-}cls :: 'v\ clause \Rightarrow ('v, nat, 'v\ clause)\ twl\text{-}state \Rightarrow$
 $('v, nat, 'v\ clause)\ twl\text{-}state$

where

$add\text{-}learned\text{-}cls\ C\ S =$
 $TWL\text{-}State\ (trail\ S)\ (init\text{-}clss\ S)\ (\{\#watch\ S\ C\#\} + learned\text{-}clss\ S)\ (backtrack\text{-}lvl\ S)$
 $(conflicting\ S)$

definition

$remove\text{-}cls :: 'v\ clause \Rightarrow ('v, nat, 'v\ clause)\ twl\text{-}state \Rightarrow ('v, nat, 'v\ clause)\ twl\text{-}state$

where

$remove\text{-}cls\ C\ S =$
 $TWL\text{-}State\ (trail\ S)\ (filter\text{-}mset\ (\lambda D. \text{raw}\text{-}clause\ D \neq C)\ (init\text{-}clss\ S))$
 $(filter\text{-}mset\ (\lambda D. \text{raw}\text{-}clause\ D \neq C)\ (learned\text{-}clss\ S))\ (backtrack\text{-}lvl\ S)$
 $(conflicting\ S)$

definition $init\text{-}state :: 'v\ clauses \Rightarrow ('v, nat, 'v\ clause)\ twl\text{-}state$ **where**

$init\text{-}state\ N = fold\ add\text{-}init\text{-}cls\ (linearize\ N)\ (TWL\text{-}State\ []\ \{\#\}\ \{\#\}\ 0\ C\text{-}True)$

lemma $unchanged\text{-}fold\text{-}add\text{-}init\text{-}cls$:

$trail\ (fold\ add\text{-}init\text{-}cls\ Cs\ (TWL\text{-}State\ M\ N\ U\ k\ C)) = M$
 $learned\text{-}clss\ (fold\ add\text{-}init\text{-}cls\ Cs\ (TWL\text{-}State\ M\ N\ U\ k\ C)) = U$
 $backtrack\text{-}lvl\ (fold\ add\text{-}init\text{-}cls\ Cs\ (TWL\text{-}State\ M\ N\ U\ k\ C)) = k$
 $conflicting\ (fold\ add\text{-}init\text{-}cls\ Cs\ (TWL\text{-}State\ M\ N\ U\ k\ C)) = C$
by $(induct\ Cs\ arbitrary: N)\ (auto\ simp: add\text{-}init\text{-}cls\text{-}def)$

lemma $unchanged\text{-}init\text{-}state[simp]$:

$trail\ (init\text{-}state\ N) = []$
 $learned\text{-}clss\ (init\text{-}state\ N) = \{\#\}$
 $backtrack\text{-}lvl\ (init\text{-}state\ N) = 0$
 $conflicting\ (init\text{-}state\ N) = C\text{-}True$

unfolding $init\text{-}state\text{-}def$ **by** $(rule\ unchanged\text{-}fold\text{-}add\text{-}init\text{-}cls)+$

lemma $clauses\text{-}init\text{-}fold\text{-}add\text{-}init$:

$no\text{-}dup\ M \implies$
 $image\text{-}mset\ raw\text{-}clause\ (init\text{-}clss\ (fold\ add\text{-}init\text{-}cls\ Cs\ (TWL\text{-}State\ M\ N\ U\ k\ C))) =$
 $mset\ Cs + image\text{-}mset\ raw\text{-}clause\ N$
by $(induct\ Cs\ arbitrary: N)\ (auto\ simp: add.assoc\ add\text{-}init\text{-}cls\text{-}def\ clause\text{-}watch)$

lemma $init\text{-}clss\text{-}init\text{-}state[simp]$: $image\text{-}mset\ raw\text{-}clause\ (init\text{-}clss\ (init\text{-}state\ N)) = N$

unfolding $init\text{-}state\text{-}def$ **by** $(simp\ add: clauses\text{-}init\text{-}fold\text{-}add\text{-}init\ linearize)$

definition $update\text{-}backtrack\text{-}lvl$ **where**

$update\text{-}backtrack\text{-}lvl\ k\ S =$

TWL-State (*trail S*) (*init-clss S*) (*learned-clss S*) *k* (*conflicting S*)

definition *update-conflicting* **where**

update-conflicting C S = *TWL-State* (*trail S*) (*init-clss S*) (*learned-clss S*) (*backtrack-lvl S*) *C*

definition *tl-trail* **where**

tl-trail S =

TWL-State (*tl (trail S)*) (*init-clss S*) (*learned-clss S*) (*backtrack-lvl S*) (*conflicting S*)

definition *restart'* **where**

restart' S = *TWL-State* [] (*init-clss S*) (*restart-learned S*) 0 *C-True*

sublocale *state_W* *trail raw-init-clss raw-learned-clss backtrack-lvl conflicting*

cons-trail tl-trail add-init-cls add-learned-cls remove-cls update-backtrack-lvl

update-conflicting init-state restart'

apply *unfold-locales*

apply (*simp-all add: add-init-cls-def add-learned-cls-def clause-rewatch clause-watch*

cons-trail-def remove-cls-def restart'-def tl-trail-def update-backtrack-lvl-def

update-conflicting-def)

apply (*rule image-mset-subseteq-mono[OF restart-learned]*)

done

sublocale *cdcl_W-ops* *trail raw-init-clss raw-learned-clss backtrack-lvl conflicting*

cons-trail tl-trail add-init-cls add-learned-cls remove-cls update-backtrack-lvl

update-conflicting init-state restart'

by *unfold-locales*

interpretation *cdcl_{NOT}*: *cdcl_{NOT}-merge-bj-learn-ops convert-trail-from-W o trail clauses*

$\lambda L S. \text{cons-trail } (\text{convert-marked-lit-from-NOT } L) S$

$\lambda S. \text{tl-trail } S$

$\lambda C S. \text{add-learned-cls } C S$

$\lambda C S. \text{remove-cls } C S$

$\lambda L S. \text{lit-of } L \in \text{fst } \text{'candidates-propagate } S$

$\lambda S. \text{conflicting } S = C\text{-True}$

$\lambda C L S. C + \{\#L\# \} \in \text{candidates-conflict } S \wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$

by *unfold-locales*

end

Lifting to the abstract state.

context *abstract-twl*

begin

declare *state-simp*[*simp del*]

abbreviation *cons-trail-twl* **where**

cons-trail-twl L S \equiv *twl-of-rough-state* (*cons-trail L (rough-state-of-twl S)*)

lemma *wf-twl-state-cons-trail*:

undefined-lit (trail S) (lit-of L) \implies wf-twl-state S \implies wf-twl-state (cons-trail L S)

unfolding *wf-twl-state-def* **by** (*auto simp: cons-trail-def wf-rewatch defined-lit-map*)

lemma *rough-state-of-twl-cons-trail*:

undefined-lit (trail-twl S) (lit-of L) \implies

rough-state-of-twl (cons-trail-twl L S) = cons-trail L (rough-state-of-twl S)

using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-state-cons-trail* **by** *blast*

abbreviation *add-init-cls-twl* **where**

add-init-cls-twl C S \equiv *twl-of-rough-state (add-init-cls C (rough-state-of-twl S))*

lemma *wf-twl-add-init-cls: wf-twl-state S \implies wf-twl-state (add-init-cls L S)*

unfolding *wf-twl-state-def* **by** (*auto simp: wf-watch add-init-cls-def split: split-if-asm*)

lemma *rough-state-of-twl-add-init-cls:*

rough-state-of-twl (add-init-cls-twl L S) = add-init-cls L (rough-state-of-twl S)

using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-add-init-cls* **by** *blast*

abbreviation *add-learned-cls-twl* **where**

add-learned-cls-twl C S \equiv *twl-of-rough-state (add-learned-cls C (rough-state-of-twl S))*

lemma *wf-twl-add-learned-cls: wf-twl-state S \implies wf-twl-state (add-learned-cls L S)*

unfolding *wf-twl-state-def* **by** (*auto simp: wf-watch add-learned-cls-def split: split-if-asm*)

lemma *rough-state-of-twl-add-learned-cls:*

rough-state-of-twl (add-learned-cls-twl L S) = add-learned-cls L (rough-state-of-twl S)

using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-add-learned-cls* **by** *blast*

abbreviation *remove-cls-twl* **where**

remove-cls-twl C S \equiv *twl-of-rough-state (remove-cls C (rough-state-of-twl S))*

lemma *wf-twl-remove-cls: wf-twl-state S \implies wf-twl-state (remove-cls L S)*

unfolding *wf-twl-state-def* **by** (*auto simp: wf-watch remove-cls-def split: split-if-asm*)

lemma *rough-state-of-twl-remove-cls:*

rough-state-of-twl (remove-cls-twl L S) = remove-cls L (rough-state-of-twl S)

using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-remove-cls* **by** *blast*

abbreviation *init-state-twl* **where**

init-state-twl N \equiv *twl-of-rough-state (init-state N)*

lemma *wf-twl-state-wf-twl-state-fold-add-init-cls:*

assumes *wf-twl-state S*

shows *wf-twl-state (fold add-init-cls N S)*

using *assms apply (induction N arbitrary: S)*

apply (*auto simp: wf-twl-state-def*) \square

by (*simp add: wf-twl-add-init-cls*)

lemma *wf-twl-state-epsilon-state[simp]:*

wf-twl-state (TWL-State [] {#} {#} 0 C-True)

by (*auto simp: wf-twl-state-def*)

lemma *wf-twl-init-state: wf-twl-state (init-state N)*

unfolding *init-state-def* **by** (*auto intro!: wf-twl-state-wf-twl-state-fold-add-init-cls*)

lemma *rough-state-of-twl-init-state:*

rough-state-of-twl (init-state-twl N) = init-state N

by (*simp add: twl-of-rough-state-inverse wf-twl-init-state*)

abbreviation *tl-trail-twl* **where**

tl-trail-twl S \equiv *twl-of-rough-state (tl-trail (rough-state-of-twl S))*

lemma *wf-twl-state-tl-trail*: $wf\text{-}twl\text{-}state\ S \implies wf\text{-}twl\text{-}state\ (tl\text{-}trail\ S)$
by (*simp* *add*: *twl-of-rough-state-inverse* *wf-twl-init-state* *wf-twl-cls-wf-twl-cls-tl*
tl-trail-def *wf-twl-state-def* *distinct-tl* *map-tl*)

lemma *rough-state-of-twl-tl-trail*:
 $rough\text{-}state\text{-}of\text{-}twl\ (tl\text{-}trail\text{-}twl\ S) = tl\text{-}trail\ (rough\text{-}state\text{-}of\text{-}twl\ S)$
using *rough-state-of-twl* *twl-of-rough-state-inverse* *wf-twl-state-tl-trail* **by** *blast*

abbreviation *update-backtrack-lvl-twl* **where**
 $update\text{-}backtrack\text{-}lvl\text{-}twl\ k\ S \equiv twl\text{-}of\text{-}rough\text{-}state\ (update\text{-}backtrack\text{-}lvl\ k\ (rough\text{-}state\text{-}of\text{-}twl\ S))$

lemma *wf-twl-state-update-backtrack-lvl*:
 $wf\text{-}twl\text{-}state\ S \implies wf\text{-}twl\text{-}state\ (update\text{-}backtrack\text{-}lvl\ k\ S)$
unfolding *wf-twl-state-def* **by** (*auto* *simp*: *update-backtrack-lvl-def*)

lemma *rough-state-of-twl-update-backtrack-lvl*:
 $rough\text{-}state\text{-}of\text{-}twl\ (update\text{-}backtrack\text{-}lvl\text{-}twl\ k\ S) = update\text{-}backtrack\text{-}lvl\ k\ (rough\text{-}state\text{-}of\text{-}twl\ S)$
using *rough-state-of-twl* *twl-of-rough-state-inverse* *wf-twl-state-update-backtrack-lvl* **by** *fast*

abbreviation *update-conflicting-twl* **where**
 $update\text{-}conflicting\text{-}twl\ k\ S \equiv twl\text{-}of\text{-}rough\text{-}state\ (update\text{-}conflicting\ k\ (rough\text{-}state\text{-}of\text{-}twl\ S))$

lemma *wf-twl-state-update-conflicting*:
 $wf\text{-}twl\text{-}state\ S \implies wf\text{-}twl\text{-}state\ (update\text{-}conflicting\ k\ S)$
unfolding *wf-twl-state-def* **by** (*auto* *simp*: *update-conflicting-def*)

lemma *rough-state-of-twl-update-conflicting*:
 $rough\text{-}state\text{-}of\text{-}twl\ (update\text{-}conflicting\text{-}twl\ k\ S) = update\text{-}conflicting\ k\ (rough\text{-}state\text{-}of\text{-}twl\ S)$
using *rough-state-of-twl* *twl-of-rough-state-inverse* *wf-twl-state-update-conflicting* **by** *fast*

abbreviation *raw-clauses-twl* **where**
 $raw\text{-}clauses\text{-}twl\ S \equiv clauses\ (rough\text{-}state\text{-}of\text{-}twl\ S)$

abbreviation *restart-twl* **where**
 $restart\text{-}twl\ S \equiv twl\text{-}of\text{-}rough\text{-}state\ (restart'\ (rough\text{-}state\text{-}of\text{-}twl\ S))$

lemma *wf-wf-restart'*: $wf\text{-}twl\text{-}state\ S \implies wf\text{-}twl\text{-}state\ (restart'\ S)$
unfolding *restart'-def* *wf-twl-state-def* **apply** *standard*
apply *clarify*
apply (*rename-tac* *x*)
apply (*subgoal-tac* *wf-twl-cls* (*trail* *S*) *x*)
apply (*case-tac* *x*)
using *restart-learned* **by** *fastforce+*

lemma *rough-state-of-twl-restart-twl*:
 $rough\text{-}state\text{-}of\text{-}twl\ (restart\text{-}twl\ S) = restart'\ (rough\text{-}state\text{-}of\text{-}twl\ S)$
by (*simp* *add*: *twl-of-rough-state-inverse* *wf-wf-restart'*)

interpretation *cdcl_{NOT}-twl-NOT*: *dpll-state*
 $convert\text{-}trail\text{-}from\text{-}W\ o\ trail\text{-}twl\ raw\text{-}clauses\text{-}twl$
 $\lambda L\ S.\ cons\text{-}trail\text{-}twl\ (convert\text{-}marked\text{-}lit\text{-}from\text{-}NOT\ L)\ S$

$\lambda S. \text{tl-trail-twl } S$
 $\lambda C S. \text{add-learned-cls-twl } C S$
 $\lambda C S. \text{remove-cls-twl } C S$
apply *unfold-locales*
 apply (*simp add: rough-state-of-twl-cons-trail*)
 apply (*metis comp-apply rough-state-of-twl-tl-trail tl-trail*)
 apply (*metis comp-def rough-state-of-twl-add-learned-cls trail-add-cls_{NOT}*)
 apply (*metis comp-apply rough-state-of-twl-remove-cls trail-remove-cls*)
 apply (*simp add: rough-state-of-twl-cons-trail*)
 apply (*metis clauses-tl-trail rough-state-of-twl-tl-trail*)
 apply (*simp add: rough-state-of-twl-add-learned-cls*)
using *clauses-remove-cls_{NOT} rough-state-of-twl-remove-cls* **by** *presburger*

interpretation *cdcl_{NOT}-twl: state_W*

trail-twl
init-clss-twl
learned-clss-twl
backtrack-lvl-twl
conflicting-twl
cons-trail-twl
tl-trail-twl
add-init-cls-twl
add-learned-cls-twl
remove-cls-twl
update-backtrack-lvl-twl
update-conflicting-twl
init-state-twl
restart-twl
apply *unfold-locales*
by (*simp-all add: rough-state-of-twl-cons-trail rough-state-of-twl-tl-trail*
 rough-state-of-twl-add-init-cls rough-state-of-twl-add-learned-cls rough-state-of-twl-remove-cls
 rough-state-of-twl-update-backtrack-lvl rough-state-of-twl-update-conflicting
 rough-state-of-twl-init-state rough-state-of-twl-restart-twl learned-clss-restart-state)

interpretation *cdcl_{NOT}-twl: cdcl_W-ops*

trail-twl
init-clss-twl
learned-clss-twl
backtrack-lvl-twl
conflicting-twl
cons-trail-twl
tl-trail-twl
add-init-cls-twl
add-learned-cls-twl
remove-cls-twl
update-backtrack-lvl-twl
update-conflicting-twl
init-state-twl
restart-twl
by *unfold-locales*

abbreviation *state-eq-twl* (**infix** $\sim \text{TWL } 51$) **where**
state-eq-twl $S S' \equiv \text{state-eq } (\text{rough-state-of-twl } S) (\text{rough-state-of-twl } S')$

notation $cdcl_{NOT}\text{-}twl.\text{state-eq}(\text{infix } \sim 51)$

declare $cdcl_{NOT}\text{-}twl.\text{state-simp}[simp\ del]$

definition *propagate-twl* **where**

propagate-twl $S\ S' \longleftrightarrow$

$(\exists L\ C. (L, C) \in \text{candidates-propagate-twl } S$
 $\wedge S' \sim \text{TWL cons-trail-twl (Propagated } L\ C) S$
 $\wedge \text{conflicting-twl } S = C\text{-True})$

lemma *propagate-twl-iff-propagate*:

assumes *inv*: $cdcl_W\text{-all-struct-inv (rough-state-of-twl } S)$

shows $cdcl_{NOT}\text{-}twl.\text{propagate } S\ T \longleftrightarrow \text{propagate-twl } S\ T$ (**is** $?P \longleftrightarrow ?T$)

proof

assume $?P$

then obtain $C\ L$ **where**

conflicting $(\text{rough-state-of-twl } S) = C\text{-True}$ **and**
 $CL\text{-Clauses: } C + \{\#L\# \} \in \# \text{ } cdcl_{NOT}\text{-}twl.\text{clauses } S$ **and**
 $tr\text{-CNot: } \text{trail-twl } S \models_{as} C\text{Not } C$ **and**
 $undef\text{-lot: } \text{undefined-lit } (\text{trail-twl } S) L$ **and**
 $T \sim \text{cons-trail-twl (Propagated } L\ (C + \{\#L\# \})) S$

unfolding $cdcl_{NOT}\text{-}twl.\text{propagate.simps}$ **by** *auto*

have $\text{distinct-mset } (C + \{\#L\# \})$

using *inv* $CL\text{-Clauses}$ **unfolding** $cdcl_W\text{-all-struct-inv-def}$ $\text{distinct-cdcl}_W\text{-state-def}$
 $cdcl_{NOT}\text{-}twl.\text{clauses-def}$ $\text{distinct-mset-set-def}$
by (*metis* $(\text{no-types, lifting})$ add-gr-0 $\text{mem-set-mset-iff plus-multiset.rep-eq}$)

then have $C\text{-L-L: } \text{mset-set } (\text{set-mset } (C + \{\#L\# \}) - \{L\}) = C$

by (*metis* $Un\text{-insert-right}$ $\text{add-diff-cancel-left'}$ $\text{add-diff-cancel-right'}$
 $\text{distinct-mset-set-mset-ident}$ finite-set-mset insert-absorb2 $\text{mset-set.insert-remove}$
 set-mset-single set-mset-union)

have $(L, C + \{\#L\# \}) \in \text{candidates-propagate-twl } S$

apply (*rule* $\text{wf-candidates-propagate-complete}$)

using *rough-state-of-twl* **apply** *auto*[]

using $CL\text{-Clauses}$ $cdcl_{NOT}\text{-}twl.\text{clauses-def}$ **apply** *auto*[]

apply *simp*

using $C\text{-L-L}$ $tr\text{-CNot}$ **apply** *simp*

using *undef-lot* **apply** *blast*

done

show $?T$ **unfolding** *propagate-twl-def*

apply (*rule* $\text{exI[of - } L]$, *rule* $\text{exI[of - } C + \{\#L\# \}]$)

apply (*auto* *simp*: $\langle (L, C + \{\#L\# \}) \in \text{candidates-propagate-twl } S \rangle$

$\langle \text{conflicting } (\text{rough-state-of-twl } S) = C\text{-True} \rangle$)

using $\langle T \sim \text{cons-trail-twl (Propagated } L\ (C + \{\#L\# \})) S \rangle$ $cdcl_{NOT}\text{-}twl.\text{state-eq-backtrack-lvl}$

$cdcl_{NOT}\text{-}twl.\text{state-eq-conflicting}$ $cdcl_{NOT}\text{-}twl.\text{state-eq-init-clss}$

$cdcl_{NOT}\text{-}twl.\text{state-eq-learned-clss}$ $cdcl_{NOT}\text{-}twl.\text{state-eq-trail state-eq-def}$ **by** *blast*

next

assume $?T$

then obtain $L\ C$ **where**

$LC: (L, C) \in \text{candidates-propagate-twl } S$ **and**

$T: T \sim \text{TWL cons-trail-twl (Propagated } L\ C) S$ **and**

$\text{confl: } \text{conflicting } (\text{rough-state-of-twl } S) = C\text{-True}$

unfolding *propagate-twl-def* **by** *auto*

have $[simp]: C - \{\#L\# \} + \{\#L\# \} = C$

using LC **unfolding** *candidates-propagate-def*

by *clarify* (*metis* add.commute $\text{add-diff-cancel-right'}$ count-diff insert-DiffM
 multi-member-last not-gr0 zero-diff)

```

have C ∈# raw-clauses-tw1 S
  using LC unfolding candidates-propagate-def clauses-def by auto
then have distinct-mset C
  using inv unfolding cdclW-all-struct-inv-def distinct-cdclW-state-def
  cdclNOT-tw1.clauses-def distinct-mset-set-def clauses-def by auto
then have C-L-L: mset-set (set-mset C - {L}) = C - {#L#}
  by (metis ⟨C - {#L#} + {#L#} = C⟩ add-left-imp-eq diff-single-trivial
    distinct-mset-set-mset-ident finite-set-mset mem-set-mset-iff mset-set.remove
    multi-self-add-other-not-self union-commute)

show ?P
  apply (rule cdclNOT-tw1.propagate.intros[of - trail-tw1 S init-clss-tw1 S
    learned-clss-tw1 S backtrack-lvl-tw1 S C - {#L#} L])
    using confl apply auto[]
    using LC unfolding candidates-propagate-def apply (auto simp: cdclNOT-tw1.clauses-def)[]
    using wf-candidates-propagate-sound[OF - LC] rough-state-of-tw1 apply (simp add: C-L-L)
    using wf-candidates-propagate-sound[OF - LC] rough-state-of-tw1 apply simp
    using T unfolding cdclNOT-tw1.state-eq-def state-eq-def by auto
qed

definition conflict-tw1 where
  conflict-tw1 S S'  $\longleftrightarrow$ 
    (∃ C. C ∈ candidates-conflict-tw1 S
    ∧ S' ∼TWL update-conflicting-tw1 (C-Clause C) S
    ∧ conflicting-tw1 S = C-True)

lemma conflict-tw1-iff-conflict:
  assumes inv: cdcl-all-struct-inv (rough-state-of-tw1 S)
  shows cdclNOT-tw1.conflict S T  $\longleftrightarrow$  conflict-tw1 S T (is ?C  $\longleftrightarrow$  ?T)
proof
  assume ?C
  then obtain M N U k C where
    S: state (rough-state-of-tw1 S) = (M, N, U, k, C-True) and
    C: C ∈# cdclNOT-tw1.clauses S and
    M-C: M ⊨as CNot C and
    T: T ∼ update-conflicting-tw1 (C-Clause C) S
  by auto
  have C ∈ candidates-conflict-tw1 S
  apply (rule wf-candidates-conflict-complete)
  apply simp
  using C apply (auto simp: cdclNOT-tw1.clauses-def)[]
  using M-C S by auto
  moreover have T ∼TWL tw1-of-rough-state (update-conflicting (C-Clause C) (rough-state-of-tw1 S))
  using T unfolding state-eq-def cdclNOT-tw1.state-eq-def by auto
  ultimately show ?T
  using S unfolding conflict-tw1-def by auto
next
  assume ?T
  then obtain C where
    C: C ∈ candidates-conflict-tw1 S and
    T: T ∼TWL update-conflicting-tw1 (C-Clause C) S and
    confl: conflicting-tw1 S = C-True
  unfolding conflict-tw1-def by auto
  have C ∈# cdclNOT-tw1.clauses S
  using C unfolding candidates-conflict-def cdclNOT-tw1.clauses-def by auto

```

moreover have *trail-tw* $S \models_{as} C \text{Not } C$
using *wf-candidates-conflict-sound* [*OF* - *C*] **by** *auto*
ultimately show $?C$ **apply** –
apply (*rule* *cdcl*_{NOT}-*twl.conflict.conflict-rule* [*of* - - - - *C*])
using *confl* *T* **unfolding** *state-eq-def* *cdcl*_{NOT}-*twl.state-eq-def* **by** *auto*
qed

end

definition *pull* :: ('a \Rightarrow bool) \Rightarrow 'a list \Rightarrow 'a list **where**
pull *p* *xs* = *filter* *p* *xs* @ *filter* (*Not* o *p*) *xs*

lemma *set-pull*[*simp*]: *set* (*pull* *p* *xs*) = *set* *xs*
unfolding *pull-def* **by** *auto*

lemma *mset-pull*[*simp*]: *mset* (*pull* *p* *xs*) = *mset* *xs*
by (*simp* *add*: *pull-def* *mset-filter-compl*)

lemma *mset-take-pull-sorted-list-of-set-subseteq*:
mset (*take* *n* (*pull* *p* (*sorted-list-of-set* (*set-mset* *A*)))) $\subseteq \#$ *A*
by (*metis* *mset-pull* *mset-set-set-mset-subseteq* *mset-sorted-list-of-set* *mset-take-subseteq*
subset-mset.dual-order.trans)

definition *watch-nat* :: (nat, nat, nat clause) *twl-state* \Rightarrow nat clause \Rightarrow nat *twl-clause* **where**
watch-nat *S* *C* =
 (let
C' = *remdups* (*sorted-list-of-set* (*set-mset* *C*));
negation-not-assigned = *filter* ($\lambda L. -L \notin \text{ lits-of } (\text{trail } S)$) *C'*;
negation-assigned-sorted-by-trail = *filter* ($\lambda L. L \in \# C$) (*map* ($\lambda L. -\text{lit-of } L$) (*trail* *S*));
W = *take* 2 (*negation-not-assigned* @ *negation-assigned-sorted-by-trail*);
UW = *sorted-list-of-multiset* (*C* - *mset* *W*)
 in *TWL-Clause* (*mset* *W*) (*mset* *UW*))

definition

rewatch-nat ::
 (nat, nat, nat literal multiset) *marked-lit* \Rightarrow (nat, nat, nat clause) *twl-state* \Rightarrow nat *twl-clause* \Rightarrow nat
twl-clause

where

rewatch-nat *L* *S* *C* =
 (if - *lit-of* *L* $\in \#$ *watched* *C* then
 case *filter* ($\lambda L'. L' \notin \# \text{ watched } C \wedge -L' \notin \text{ lits-of } (L \# \text{ trail } S)$)
 (*sorted-list-of-multiset* (*unwatched* *C*)) of
 [] \Rightarrow *C*
 | *L' # -* \Rightarrow
TWL-Clause (*watched* *C* - {*#* - *lit-of* *L* #} + {*#* *L' #*}) (*unwatched* *C* - {*#* *L' #*} + {*#* - *lit-of*
L #})
 else
C)

thm *rev-cases*

lemma *list-cases2*:

fixes *l* :: 'a list

assumes

l = [] \Longrightarrow *P* **and**

$\bigwedge x. l = [x] \Longrightarrow$ *P* **and**

$\bigwedge x y. l = [x, y] \implies P$ **and**
 $\bigwedge x y xs. l = x \# y \# xs \implies P$
shows P
by (*metis* *assms*(1) *assms*(2) *assms*(4) *list.collapse*)

lemma XXX:
assumes $[L \leftarrow P . L \in \# C] = l$
shows $\forall x \in \text{set } l. x \in \text{set } P \wedge x \in \# C$
using *assms* **by** *auto*

lemma XXX':
assumes $[L \leftarrow P . Q L] = l$
shows $\forall x \in \text{set } l. x \in \text{set } P \wedge Q x$
using *assms* **by** *auto*

lemma *no-dup-filter-diff*:
assumes *n-d*: *no-dup* M **and** H : $[L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) M. L \in \# C] = l$
shows *distinct* l
unfolding $H[\text{symmetric}]$
apply (*rule distinct-filter*)
using *n-d* **by** (*induction* M) *auto*

lemma *mset-intersection-inclusion*: $A + (B - A) = B \longleftrightarrow A \subseteq \# B$
apply (*rule iffI*)
apply (*metis mset-le-add-left*)
by (*auto simp: ac-simps multiset-eq-iff subseteq-mset-def*)

lemma *clause-watch-nat*: *no-dup* $(\text{trail } S) \implies \text{raw-clause } (\text{watch-nat } S C) = C$
apply (*simp add: watch-nat-def Let-def*
mset-intersection-inclusion)
apply (*cases* $[L \leftarrow \text{remdups } (\text{sorted-list-of-set } (\text{set-mset } C)). - L \notin \text{lits-of } (\text{trail } S)]$ *rule: list-cases2*;
cases $[L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) (\text{trail } S) . L \in \# C]$ *rule: list-cases2*)
apply (*auto dest!: XXX' simp: ac-simps multiset-eq-iff*)[]

apply (*auto dest: XXX' dest: no-dup-filter-diff simp: ac-simps multiset-eq-iff*)[1]
apply *simp*
apply (*auto dest: XXX' dest: no-dup-filter-diff simp: ac-simps multiset-eq-iff*)[]
sorry

lemma *distinct-pull*[*simp*]: *distinct* $(\text{pull } p xs) = \text{distinct } xs$
unfolding *pull-def* **by** (*induct* xs) *auto*

lemma *falsified-watched-imp-unwatched-falsified*:
assumes
watched: $L \in \text{set } (\text{take } n (\text{pull } (\text{Not} \circ \text{fls}) (\text{sorted-list-of-set } (\text{set-mset } C))))$ **and**
falsified: *fls* L **and**
not-watched: $L' \notin \text{set } (\text{take } n (\text{pull } (\text{Not} \circ \text{fls}) (\text{sorted-list-of-set } (\text{set-mset } C))))$ **and**
unwatched: $L' \in \# C - \text{mset } (\text{take } n (\text{pull } (\text{Not} \circ \text{fls}) (\text{sorted-list-of-set } (\text{set-mset } C))))$
shows *fls* L'
proof –
let $?Ls = \text{sorted-list-of-set } (\text{set-mset } C)$
let $?W = \text{take } n (\text{pull } (\text{Not} \circ \text{fls}) ?Ls)$

have $n > \text{length } (\text{filter } (\text{Not} \circ \text{fls}) ?Ls)$

```

using watched falsified
unfolding pull-def comp-def
apply auto
  using in-set-takeD apply fastforce
  by (metis grOI length-greater-0-conv length-pos-if-in-set take-0 zero-less-diff)
then have  $\bigwedge L. L \in \text{set } ?Ls \implies \neg \text{fls } L \implies L \in \text{set } ?W$ 
  unfolding pull-def by auto
then show ?thesis
  by (metis Multiset.diff-le-self finite-set-mset mem-set-mset-iff mset-leD not-watched
    sorted-list-of-set unwatched)
qed

lemma wf-watch-nat: no-dup (trail S)  $\implies$  wf-twl-cls (trail S) (watch-nat S C)
  apply (simp only: watch-nat-def Let-def partition-filter-conv case-prod-beta fst-conv snd-conv)
  unfolding wf-twl-cls.simps
  apply (intro conjI)
  apply clarsimp+
  using falsified-watched-imp-unwatched-falsified[unfolded comp-def]

sorry

lemma filter-sorted-list-of-multiset-eqD:
  assumes  $[x \leftarrow \text{sorted-list-of-multiset } A. p \ x] = x \# xs$  (is ?comp = -)
  shows  $x \in \# A$ 
proof -
  have  $x \in \text{set } ?comp$ 
  using assms by simp
  then have  $x \in \text{set } (\text{sorted-list-of-multiset } A)$ 
  by simp
  then show  $x \in \# A$ 
  by simp
qed

lemma clause-rewatch-nat: raw-clause (rewatch-nat L S C) = raw-clause C
  apply (auto simp: rewatch-nat-def Let-def split: list.split)
  apply (subst subset-mset.add-diff-assoc2, simp)
  apply (subst subset-mset.add-diff-assoc2, simp)
  apply (subst subset-mset.add-diff-assoc2)
  apply (auto dest: filter-sorted-list-of-multiset-eqD)
  by (metis (no-types, lifting) add.assoc add-diff-cancel-right' filter-sorted-list-of-multiset-eqD
    insert-DiffM mset-leD mset-le-add-left)

lemma filter-sorted-list-of-multiset-Nil:
 $[x \leftarrow \text{sorted-list-of-multiset } M. p \ x] = [] \longleftrightarrow (\forall x \in \# M. \neg p \ x)$ 
  by auto (metis empty-iff filter-set list.set(1) mem-set-mset-iff member-filter
    set-sorted-list-of-multiset)

lemma filter-sorted-list-of-multiset-ConsD:
 $[x \leftarrow \text{sorted-list-of-multiset } M. p \ x] = x \# xs \implies p \ x$ 
  by (metis filter-set insert-iff list.set(2) member-filter)

lemma mset-minus-single-eq-empty:
 $a - \{\#b\} = \{\#\} \longleftrightarrow a = \{\#b\} \vee a = \{\#\}$ 
  by (metis Multiset.diff-cancel add.right-neutral diff-single-eq-union)

```

diff-single-trivial zero-diff)

```

lemma wf-rewatch-nat':
  assumes wf: wf-twl-cls (trail S) C
  shows wf-twl-cls (L # trail S) (rewatch-nat L S C)
using filter-sorted-list-of-multiset-Nil[simp]
proof (cases - lit-of L ∈# watched C)
  case falsified: True

  let ?unwatched-nonfalsified =
    [L' ← sorted-list-of-multiset (unwatched C). L' ∉# watched C ∧ - L' ∈ lits-of (L # trail S)]

  show ?thesis
proof (cases ?unwatched-nonfalsified)
  case Nil
  show ?thesis
    unfolding rewatch-nat-def
    using falsified Nil apply auto
    apply (case-tac C)
    apply auto
    using local.wf wf-twl-cls.simps apply blast
    using local.wf wf-twl-cls.simps apply blast
    sorry
  next
  case (Cons L' Ls)
  show ?thesis
    using wf
    unfolding rewatch-nat-def
    using falsified Cons

    sorry
  qed
next
  case False
  have wf-twl-cls (L # trail S) C
  using wf

  sorry
then show ?thesis
  unfolding rewatch-nat-def using False by simp
qed

```

```

interpretation abstract-twl watch-nat rewatch-nat sorted-list-of-multiset learned-clss
apply unfold-locales
apply (rule clause-watch-nat; simp)
apply (rule wf-watch-nat; simp)
apply (rule clause-rewatch-nat)
apply (rule wf-rewatch-nat', simp)
apply (rule mset-sorted-list-of-multiset)
apply (rule subset-mset.order-refl)
oops

```

```

end
theory Prop-Superposition
imports Partial-Clausal-Logic ../lib/Herbrand-Interpretation
begin
sledgehammer-params[verbose]
no-notation Herbrand-Interpretation.true-cls (infix  $\models$  50)
notation Herbrand-Interpretation.true-cls (infix  $\models_h$  50)

no-notation Herbrand-Interpretation.true-clss (infix  $\models_s$  50)
notation Herbrand-Interpretation.true-clss (infix  $\models_{hs}$  50)

lemma herbrand-interp-iff-partial-interp-cls:
   $S \models_h C \longleftrightarrow \{Pos\ P|P. P \in S\} \cup \{Neg\ P|P. P \notin S\} \models C$ 
  unfolding Herbrand-Interpretation.true-cls-def Partial-Clausal-Logic.true-cls-def
  by auto

lemma herbrand-consistent-interp:
  consistent-interp ( $\{Pos\ P|P. P \in S\} \cup \{Neg\ P|P. P \notin S\}$ )
  unfolding consistent-interp-def by auto

lemma herbrand-total-over-set:
  total-over-set ( $\{Pos\ P|P. P \in S\} \cup \{Neg\ P|P. P \notin S\}$ )  $T$ 
  unfolding total-over-set-def by auto

lemma herbrand-total-over-m:
  total-over-m ( $\{Pos\ P|P. P \in S\} \cup \{Neg\ P|P. P \notin S\}$ )  $T$ 
  unfolding total-over-m-def by (auto simp add: herbrand-total-over-set)

lemma herbrand-interp-iff-partial-interp-clss:
   $S \models_{hs} C \longleftrightarrow \{Pos\ P|P. P \in S\} \cup \{Neg\ P|P. P \notin S\} \models_s C$ 
  unfolding true-clss-def Ball-def herbrand-interp-iff-partial-interp-cls
  Partial-Clausal-Logic.true-clss-def by auto

definition clss-lt :: 'a::wellorder clauses  $\Rightarrow$  'a clause  $\Rightarrow$  'a clauses where
  clss-lt  $N\ C = \{D \in N. D \# \subset \# C\}$ 

notation (latex output)
  clss-lt ( $\prec^{bsup} \prec^{esup}$ )

locale selection =
  fixes  $S :: 'a\ clause \Rightarrow 'a\ clause$ 
  assumes
     $S\text{-selects-subseteq}: \bigwedge C. S\ C \leq \# C$  and
     $S\text{-selects-neg-lits}: \bigwedge C\ L. L \in \# S\ C \implies is\_neg\ L$ 

locale ground-resolution-with-selection =
  selection  $S$  for  $S :: ('a :: wellorder)\ clause \Rightarrow 'a\ clause$ 
begin

context
  fixes  $N :: 'a\ clause\ set$ 
begin

```

We do not create an equivalent of δ , but we directly defined N_C by inlining the definition.

```
function
```

```

production :: 'a clause  $\Rightarrow$  'a interp
where
  production C =
    {A. C  $\in$  N  $\wedge$  C  $\neq$  {#}  $\wedge$  Max (set-mset C) = Pos A  $\wedge$  count C (Pos A)  $\leq$  1
       $\wedge$   $\neg$  ( $\bigcup D \in \{D. D \# \subset \# C\}. production D$ )  $\models_h C \wedge S C = \{ \# \}$ 
    by auto
termination by (relation {(D, C). D  $\# \subset \# C$ }) (auto simp: wf-less-multiset)

declare production.simps[simp del]

definition interp :: 'a clause  $\Rightarrow$  'a interp where
  interp C = ( $\bigcup D \in \{D. D \# \subset \# C\}. production D$ )

lemma production-unfold:
  production C = {A. C  $\in$  N  $\wedge$  C  $\neq$  {#}  $\wedge$  Max (set-mset C) = Pos A  $\wedge$  count C (Pos A)  $\leq$  1  $\wedge$   $\neg$ 
  interp C  $\models_h C \wedge S C = \{ \# \}$ 
  unfolding interp-def by (rule production.simps)

abbreviation productive A  $\equiv$  (production A  $\neq$  { })

abbreviation produces :: 'a clause  $\Rightarrow$  'a  $\Rightarrow$  bool where
  produces C A  $\equiv$  production C = {A}

lemma producesD:
  produces C A  $\implies$  C  $\in$  N  $\wedge$  C  $\neq$  {#}  $\wedge$  Pos A = Max (set-mset C)  $\wedge$  count C (Pos A)  $\leq$  1  $\wedge$   $\neg$ 
  interp C  $\models_h C \wedge S C = \{ \# \}$ 
  unfolding production-unfold by auto

lemma produces C A  $\implies$  Pos A  $\in \# C$ 
  by (simp add: Max-in-lits producesD)

lemma interp'-def-in-set:
  interp C = ( $\bigcup D \in \{D \in N. D \# \subset \# C\}. production D$ )
  unfolding interp-def apply auto
  unfolding production-unfold apply auto
  done

lemma production-iff-produces:
  produces D A  $\longleftrightarrow$  A  $\in$  production D
  unfolding production-unfold by auto

definition Interp :: 'a clause  $\Rightarrow$  'a interp where
  Interp C = interp C  $\cup$  production C

lemma
  assumes produces C P
  shows Interp C  $\models_h C$ 
  unfolding Interp-def assms using producesD[OF assms]
  by (metis Max-in-lits Un-insert-right insertI1 pos-literal-in-imp-true-cls)

definition INTERP :: 'a interp where
  INTERP = ( $\bigcup D \in N. production D$ )

lemma interp-subseteq-Interp[simp]: interp C  $\subseteq$  Interp C

```


unfolding *Interp-def* **by** *simp*

lemma *Interp-as-UNION*: $\text{Interp } C = (\bigcup D \in \{D. D \# \subseteq \# C\}. \text{production } D)$
unfolding *Interp-def interp-def le-multiset-def* **by** *fast*

lemma *productive-not-empty*: $\text{productive } C \implies C \neq \{\#\}$
unfolding *production-unfold* **by** *auto*

lemma *productive-imp-produces-Max-literal*: $\text{productive } C \implies \text{produces } C (\text{atm-of } (\text{Max } (\text{set-mset } C)))$
unfolding *production-unfold* **by** (*auto simp del: atm-of-Max-lit*)

lemma *productive-imp-produces-Max-atom*: $\text{productive } C \implies \text{produces } C (\text{Max } (\text{atms-of } C))$
unfolding *atms-of-def Max-atm-of-set-mset-commute*[*OF productive-not-empty*]
by (*rule productive-imp-produces-Max-literal*)

lemma *produces-imp-Max-literal*: $\text{produces } C A \implies A = \text{atm-of } (\text{Max } (\text{set-mset } C))$
by (*metis Max-singleton insert-not-empty productive-imp-produces-Max-literal*)

lemma *produces-imp-Max-atom*: $\text{produces } C A \implies A = \text{Max } (\text{atms-of } C)$
by (*metis Max-singleton insert-not-empty productive-imp-produces-Max-atom*)

lemma *produces-imp-Pos-in-lits*: $\text{produces } C A \implies \text{Pos } A \in \# C$
by (*auto intro: Max-in-lits dest!: producesD*)

lemma *productive-in-N*: $\text{productive } C \implies C \in N$
unfolding *production-unfold* **by** *auto*

lemma *produces-imp-atms-leq*: $\text{produces } C A \implies B \in \text{atms-of } C \implies B \leq A$
by (*metis Max-ge finite-atms-of insert-not-empty productive-imp-produces-Max-atom singleton-inject*)

lemma *produces-imp-neg-notin-lits*: $\text{produces } C A \implies \neg \text{Neg } A \in \# C$
by (*auto intro!: pos-Max-imp-neg-notin dest: producesD simp del: not-gr0*)

lemma *less-eq-imp-interp-subseteq-interp*: $C \# \subseteq \# D \implies \text{interp } C \subseteq \text{interp } D$
unfolding *interp-def* **by** *auto* (*metis multiset-order.order.strict-trans2*)

lemma *less-eq-imp-interp-subseteq-Interp*: $C \# \subseteq \# D \implies \text{interp } C \subseteq \text{Interp } D$
unfolding *Interp-def* **using** *less-eq-imp-interp-subseteq-interp* **by** *blast*

lemma *less-imp-production-subseteq-interp*: $C \# \subset \# D \implies \text{production } C \subseteq \text{interp } D$
unfolding *interp-def* **by** *fast*

lemma *less-eq-imp-production-subseteq-Interp*: $C \# \subseteq \# D \implies \text{production } C \subseteq \text{Interp } D$
unfolding *Interp-def* **using** *less-imp-production-subseteq-interp*
by (*metis multiset-order.le-imp-less-or-eq le-supI1 sup-ge2*)

lemma *less-imp-Interp-subseteq-interp*: $C \# \subset \# D \implies \text{Interp } C \subseteq \text{interp } D$
unfolding *Interp-def*
by (*auto simp: less-eq-imp-interp-subseteq-interp less-imp-production-subseteq-interp*)

lemma *less-eq-imp-Interp-subseteq-Interp*: $C \# \subseteq \# D \implies \text{Interp } C \subseteq \text{Interp } D$
using *less-imp-Interp-subseteq-interp*
unfolding *Interp-def* **by** (*metis multiset-order.le-imp-less-or-eq le-supI2 subset-refl sup-commute*)

lemma *false-Interp-to-true-interp-imp-less-multiset*: $A \notin \text{Interp } C \implies A \in \text{interp } D \implies C \# \subseteq \# D$
using *less-eq-imp-interp-subseteq-Interp multiset-linorder.not-less* **by** *blast*

lemma *false-interp-to-true-interp-imp-less-multiset*: $A \notin \text{interp } C \implies A \in \text{interp } D \implies C \# \subseteq \# D$
using *less-eq-imp-interp-subseteq-interp multiset-linorder.not-less* **by** *blast*

lemma *false-Interp-to-true-Interp-imp-less-multiset*: $A \notin \text{Interp } C \implies A \in \text{Interp } D \implies C \# \subseteq \# D$
using *less-eq-imp-Interp-subseteq-Interp multiset-linorder.not-less* **by** *blast*

lemma *false-interp-to-true-Interp-imp-le-multiset*: $A \notin \text{interp } C \implies A \in \text{Interp } D \implies C \# \subseteq \# D$
using *less-imp-Interp-subseteq-interp multiset-linorder.not-less* **by** *blast*

lemma *interp-subseteq-INTERP*: $\text{interp } C \subseteq \text{INTERP}$
unfolding *interp-def INTERP-def* **by** (*auto simp: production-unfold*)

lemma *production-subseteq-INTERP*: $\text{production } C \subseteq \text{INTERP}$
unfolding *INTERP-def* **using** *production-unfold* **by** *blast*

lemma *Interp-subseteq-INTERP*: $\text{Interp } C \subseteq \text{INTERP}$
unfolding *Interp-def* **by** (*auto intro!: interp-subseteq-INTERP production-subseteq-INTERP*)

This lemma corresponds to theorem 2.7.6 page 66 of CW.

lemma *produces-imp-in-interp*:
assumes *a-in-c*: $\text{Neg } A \in \# C$ **and** *d*: *produces* $D A$
shows $A \in \text{interp } C$

proof –

from *d* **have** $\text{Max } (\text{set-mset } D) = \text{Pos } A$

using *production-unfold* **by** *blast*

hence $D \# \subseteq \# \{\# \text{Neg } A \# \}$

by (*auto intro: Max-pos-neg-less-multiset*)

moreover have $\{\# \text{Neg } A \# \} \# \subseteq \# C$

by (*rule less-eq-imp-le-multiset*) (*rule mset-le-single[OF a-in-c[unfolding mem-set-mset-iff]]*)

ultimately show *?thesis*

using *d* **by** (*blast dest: less-eq-imp-interp-subseteq-interp less-imp-production-subseteq-interp*)

qed

lemma *neg-notin-Interp-not-produce*: $\text{Neg } A \in \# C \implies A \notin \text{Interp } D \implies C \# \subseteq \# D \implies \neg \text{produces } D'' A$

by (*auto dest: produces-imp-in-interp less-eq-imp-interp-subseteq-Interp*)

lemma *in-production-imp-produces*: $A \in \text{production } C \implies \text{produces } C A$
by (*metis insert-absorb productive-imp-produces-Max-atom singleton-insert-inj-eq'*)

lemma *not-produces-imp-notin-production*: $\neg \text{produces } C A \implies A \notin \text{production } C$
by (*metis in-production-imp-produces*)

lemma *not-produces-imp-notin-interp*: $(\bigwedge D. \neg \text{produces } D A) \implies A \notin \text{interp } C$
unfolding *interp-def* **by** (*fast intro!: in-production-imp-produces*)

The results below corresponds to Lemma 3.4.

Nitpicking: If $D = D'$ and D is productive, $I^D \subseteq I_{D'}$ does not hold.

lemma *true-Interp-imp-general*:

assumes

c-le-d: $C \# \subseteq \# D$ **and**

d-lt-d': $D \# \subseteq \# D'$ **and**

$c\text{-at-}d$: $\text{Interp } D \models_h C$ **and**
 subs : $\text{interp } D' \subseteq (\bigcup C \in CC. \text{production } C)$
shows $(\bigcup C \in CC. \text{production } C) \models_h C$
proof (*cases* $\exists A. \text{Pos } A \in\# C \wedge A \in \text{Interp } D$)
case *True*
then obtain A **where** $a\text{-in-}c$: $\text{Pos } A \in\# C$ **and** $a\text{-at-}d$: $A \in \text{Interp } D$
by *blast*
from $a\text{-at-}d$ **have** $A \in \text{interp } D'$
using $d\text{-lt-}d'$ *less-imp-Interp-subseteq-interp* **by** *blast*
thus *?thesis*
using subs $a\text{-in-}c$ **by** (*blast dest: contra-subsetD*)
next
case *False*
then obtain A **where** $a\text{-in-}c$: $\text{Neg } A \in\# C$ **and** $A \notin \text{Interp } D$
using $c\text{-at-}d$ **unfolding** *true-cls-def* **by** *blast*
hence $\bigwedge D''. \neg \text{produces } D'' A$
using $c\text{-le-}d$ *neg-notin-Interp-not-produce* **by** *simp*
thus *?thesis*
using $a\text{-in-}c$ *subs not-produces-imp-notin-production* **by** *auto*
qed

lemma *true-Interp-imp-interp*: $C \# \subseteq \# D \implies D \# \subset \# D' \implies \text{Interp } D \models_h C \implies \text{interp } D' \models_h C$
using *interp-def true-Interp-imp-general* **by** *simp*

lemma *true-Interp-imp-Interp*: $C \# \subseteq \# D \implies D \# \subset \# D' \implies \text{Interp } D \models_h C \implies \text{Interp } D' \models_h C$
using *Interp-as-UNION interp-subseteq-Interp true-Interp-imp-general* **by** *simp*

lemma *true-Interp-imp-INTERP*: $C \# \subseteq \# D \implies \text{Interp } D \models_h C \implies \text{INTERP} \models_h C$
using *INTERP-def interp-subseteq-INTERP*
 $\text{true-Interp-imp-general}[OF \text{ - less-multiset-right-total}]$
by *simp*

lemma *true-interp-imp-general*:
assumes
 $c\text{-le-}d$: $C \# \subseteq \# D$ **and**
 $d\text{-lt-}d'$: $D \# \subset \# D'$ **and**
 $c\text{-at-}d$: $\text{interp } D \models_h C$ **and**
 subs : $\text{interp } D' \subseteq (\bigcup C \in CC. \text{production } C)$
shows $(\bigcup C \in CC. \text{production } C) \models_h C$
proof (*cases* $\exists A. \text{Pos } A \in\# C \wedge A \in \text{interp } D$)
case *True*
then obtain A **where** $a\text{-in-}c$: $\text{Pos } A \in\# C$ **and** $a\text{-at-}d$: $A \in \text{interp } D$
by *blast*
from $a\text{-at-}d$ **have** $A \in \text{interp } D'$
using $d\text{-lt-}d'$ *less-eq-imp-interp-subseteq-interp*[*OF multiset-order.less-imp-le*] **by** *blast*
thus *?thesis*
using subs $a\text{-in-}c$ **by** (*blast dest: contra-subsetD*)
next
case *False*
then obtain A **where** $a\text{-in-}c$: $\text{Neg } A \in\# C$ **and** $A \notin \text{interp } D$
using $c\text{-at-}d$ **unfolding** *true-cls-def* **by** *blast*
hence $\bigwedge D''. \neg \text{produces } D'' A$
using $c\text{-le-}d$ **by** (*auto dest: produces-imp-in-interp less-eq-imp-interp-subseteq-interp*)
thus *?thesis*
using $a\text{-in-}c$ *subs not-produces-imp-notin-production* **by** *auto*

qed

This lemma corresponds to theorem 2.7.6 page 66 of CW. Here the strict maximality is important

lemma *true-interp-imp-interp*: $C \# \subseteq \# D \implies D \# \subset \# D' \implies \text{interp } D \models_h C \implies \text{interp } D' \models_h C$
using *interp-def true-interp-imp-general* **by** *simp*

lemma *true-interp-imp-Interp*: $C \# \subseteq \# D \implies D \# \subset \# D' \implies \text{interp } D \models_h C \implies \text{Interp } D' \models_h C$
using *Interp-as-UNION interp-subseteq-Interp[of D'] true-interp-imp-general* **by** *simp*

lemma *true-interp-imp-INTERP*: $C \# \subseteq \# D \implies \text{interp } D \models_h C \implies \text{INTERP} \models_h C$
using *INTERP-def interp-subseteq-INTERP*
true-interp-imp-general[OF - less-multiset-right-total]
by *simp*

lemma *productive-imp-false-interp*: $\text{productive } C \implies \neg \text{interp } C \models_h C$
unfolding *production-unfold* **by** *auto*

This lemma corresponds to theorem 2.7.6 page 66 of CW. Here the strict maximality is important

lemma *cls-gt-double-pos-no-production*:
assumes $D: \{\#Pos P, Pos P\} \# \subset \# C$
shows $\neg \text{produces } C P$
proof –
let $?D = \{\#Pos P, Pos P\}$
note $D' = D[\text{unfolded less-multiset}_{HO}]$
consider
 $(P) \text{ count } C (Pos P) \geq 2$
 $| (Q) Q \text{ where } Q > Pos P \text{ and } Q \in \# C$
using *HOL.spec[OF HOL.conjunct2[OF D'], of Pos P]* **by** *auto*
thus *?thesis*
proof *cases*
case Q
have $Q \in \text{set-mset } C$
using $Q(2)$ **by** *(auto split: split-if-asm)*
then have $\text{Max } (\text{set-mset } C) > Pos P$
using $Q(1)$ *Max-gr-iff* **by** *blast*
thus *?thesis*
unfolding *production-unfold* **by** *auto*
next
case P
thus *?thesis*
unfolding *production-unfold* **by** *auto*
qed
qed

This lemma corresponds to theorem 2.7.6 page 66 of CW.

lemma
assumes $D: C + \{\#Neg P\} \# \subset \# D$
shows $\text{production } D \neq \{P\}$
proof –
note $D' = D[\text{unfolded less-multiset}_{HO}]$
consider
 $(P) Neg P \in \# D$
 $| (Q) Q \text{ where } Q > Neg P \text{ and } \text{count } D Q > \text{count } (C + \{\#Neg P\}) Q$
using *HOL.spec[OF HOL.conjunct2[OF D'], of Neg P]* **by** *fastforce*
thus *?thesis*

```

proof cases
  case  $Q$ 
  have  $Q \in \text{set-mset } D$ 
    using  $Q(2)$  by (auto split: split-if-asm)
  then have  $\text{Max } (\text{set-mset } D) > \text{Neg } P$ 
    using  $Q(1)$  Max-gr-iff by blast
  hence  $\text{Max } (\text{set-mset } D) > \text{Pos } P$ 
    using less-trans[of Pos P Neg P Max (set-mset D)] by auto
  thus ?thesis
    unfolding production-unfold by auto
next
  case  $P$ 
  hence  $\text{Max } (\text{set-mset } D) > \text{Pos } P$ 
    by (meson Max-ge finite-set-mset le-less-trans linorder-not-le mem-set-mset-iff
      pos-less-neg)
  thus ?thesis
    unfolding production-unfold by auto
qed
qed

```

```

lemma in-interp-is-produced:
  assumes  $P \in \text{INTERP}$ 
  shows  $\exists D. D + \{\# \text{Pos } P\} \in N \wedge \text{produces } (D + \{\# \text{Pos } P\}) P$ 
  using assms unfolding INTERP-def UN-iff production-iff-produces Ball-def
  by (metis ground-resolution-with-selection.produces-imp-Pos-in-lits insert-DiffM2
    ground-resolution-with-selection-axioms not-produces-imp-notin-production)

```

end
end

abbreviation $M\text{Max } M \equiv \text{Max } (\text{set-mset } M)$

20.1 We can now define the rules of the calculus

inductive *superposition-rules* :: '*a clause* \Rightarrow '*a clause* \Rightarrow '*a clause* \Rightarrow *bool* **where**
factoring: *superposition-rules* $(C + \{\# \text{Pos } P\} + \{\# \text{Pos } P\}) B (C + \{\# \text{Pos } P\}) \mid$
superposition-l: *superposition-rules* $(C_1 + \{\# \text{Pos } P\}) (C_2 + \{\# \text{Neg } P\}) (C_1 + C_2)$

inductive *superposition* :: '*a clauses* \Rightarrow '*a clauses* \Rightarrow *bool* **where**
superposition: $A \in N \Longrightarrow B \in N \Longrightarrow \text{superposition-rules } A B C$
 $\Longrightarrow \text{superposition } N (N \cup \{C\})$

definition *abstract-red* :: '*a::wellorder clause* \Rightarrow '*a clauses* \Rightarrow *bool* **where**
abstract-red $C N = (\text{class-lt } N C \models_p C)$

lemma *less-multiset[iff]*: $M < N \longleftrightarrow M \# \subset \# N$
unfolding *less-multiset-def* **by** *auto*

lemma *less-eq-multiset[iff]*: $M \leq N \longleftrightarrow M \# \subseteq \# N$
unfolding *less-eq-multiset-def* **by** *auto*

lemma *herbrand-true-cls-true-cls-cls-herbrand-true-cls*:
assumes
 $AB: A \models_{hs} B$ **and**
 $BC: B \models_p C$

shows $A \models_h C$
proof –
let $?I = \{Pos\ P \mid P. P \in A\} \cup \{Neg\ P \mid P. P \notin A\}$
have $B: ?I \models_s B$ **using** AB
by (*auto simp add: herbrand-interp-iff-partial-interp-clss*)

have $IH: \bigwedge I. total-over-set\ I\ (atms-of\ C) \implies total-over-m\ I\ B \implies consistent-interp\ I$
 $\implies I \models_s B \implies I \models C$ **using** BC
by (*auto simp add: true-clss-clss-def*)
show $?thesis$
unfolding *herbrand-interp-iff-partial-interp-clss*
by (*auto intro: IH[of ?I] simp add: herbrand-total-over-set herbrand-total-over-m*
herbrand-consistent-interp B)
qed

lemma *abstract-red-subset-mset-abstract-red*:
assumes
abstr: abstract-red C N and
c-lt-d: C $\subseteq\#$ D
shows *abstract-red D N*
proof –
have $\{D \in N. D \# \subset \# C\} \subseteq \{D' \in N. D' \# \subset \# D\}$
using *c-lt-d less-eq-imp-le-multiset* **by** *fastforce*
thus $?thesis$
using *abstr unfolding abstract-red-def clss-lt-def*
by (*metis (no-types, lifting) c-lt-d subset-mset.diff-add true-clss-clss-mono-r'*
true-clss-clss-subset)
qed

lemma *true-clss-clss-extended*:
assumes
 $A \models_p B$ **and**
tot: total-over-m I (A) and
cons: consistent-interp I and
 $I-A: I \models_s A$
shows $I \models B$
proof –
let $?I = I \cup \{Pos\ P \mid P. P \in atms-of\ B \wedge P \notin atms-of-s\ I\}$
have *consistent-interp ?I*
using *cons unfolding consistent-interp-def atms-of-s-def atms-of-def*
apply (*auto 1 5 simp add: image-iff*)
by (*metis atm-of-uminus literal.sel(1)*)
moreover have *total-over-m ?I (A \cup {B})*
proof –
obtain $aa :: 'a\ set \Rightarrow 'a\ literal\ set \Rightarrow 'a$ **where**
 $f2: \forall x0\ x1. (\exists v2. v2 \in x0 \wedge Pos\ v2 \notin x1 \wedge Neg\ v2 \notin x1)$
 $\longleftrightarrow (aa\ x0\ x1 \in x0 \wedge Pos\ (aa\ x0\ x1) \notin x1 \wedge Neg\ (aa\ x0\ x1) \notin x1)$
by *moura*
have $\forall a. a \notin atms-of-ms\ A \vee Pos\ a \in I \vee Neg\ a \in I$
using *tot* **by** (*simp add: total-over-m-def total-over-set-def*)
hence $aa\ (atms-of-ms\ A \cup atms-of-ms\ \{B\})\ (I \cup \{Pos\ a \mid a. a \in atms-of\ B \wedge a \notin atms-of-s\ I\})$
 $\notin atms-of-ms\ A \cup atms-of-ms\ \{B\} \vee Pos\ (aa\ (atms-of-ms\ A \cup atms-of-ms\ \{B\}))$
 $(I \cup \{Pos\ a \mid a. a \in atms-of\ B \wedge a \notin atms-of-s\ I\}) \in I$
 $\cup \{Pos\ a \mid a. a \in atms-of\ B \wedge a \notin atms-of-s\ I\}$

```

       $\vee \text{Neg } (aa \ (atms\text{-of}\text{-}ms \ A \cup atms\text{-of}\text{-}ms \ \{B\})$ 
       $(I \cup \{Pos \ a \mid a. \ a \in atms\text{-of} \ B \wedge a \notin atms\text{-of}\text{-}s \ I\}) \in I$ 
       $\cup \{Pos \ a \mid a. \ a \in atms\text{-of} \ B \wedge a \notin atms\text{-of}\text{-}s \ I\}$ 
    by auto
  hence total-over-set  $(I \cup \{Pos \ a \mid a. \ a \in atms\text{-of} \ B \wedge a \notin atms\text{-of}\text{-}s \ I\}) \ (atms\text{-of}\text{-}ms \ A \cup atms\text{-of}\text{-}ms \ \{B\})$ 
  using f2 by (meson total-over-set-def)
  thus ?thesis
    by (simp add: total-over-m-def)
  qed
moreover have ?I  $\models_s A$ 
  using I-A by auto
ultimately have ?I  $\models B$ 
  using  $\langle A \models_p B \rangle$  unfolding true-clss-clss-def by auto
thus ?thesis
oops
lemma
  assumes
    CP:  $\neg \text{clss}\text{-}lt \ N \ (\{\#C\# \} + \{\#E\# \}) \models_p \{\#C\# \} + \{\#Neg \ P\# \}$  and
     $\text{clss}\text{-}lt \ N \ (\{\#C\# \} + \{\#E\# \}) \models_p \{\#E\# \} + \{\#Pos \ P\# \} \vee \text{clss}\text{-}lt \ N \ (\{\#C\# \} + \{\#E\# \}) \models_p$ 
     $\{\#C\# \} + \{\#Neg \ P\# \}$ 
  shows  $\text{clss}\text{-}lt \ N \ (\{\#C\# \} + \{\#E\# \}) \models_p \{\#E\# \} + \{\#Pos \ P\# \}$ 
oops
locale ground-ordered-resolution-with-redundancy =
  ground-resolution-with-selection +
  fixes redundant :: 'a::wellorder clause  $\Rightarrow$  'a clauses  $\Rightarrow$  bool
  assumes
    redundant-iff-abstract:  $\text{redundant } A \ N \longleftrightarrow \text{abstract}\text{-}red \ A \ N$ 
begin
definition saturated :: 'a clauses  $\Rightarrow$  bool where
  saturated  $N \longleftrightarrow (\forall \ A \ B \ C. \ A \in N \longrightarrow B \in N \longrightarrow \neg \text{redundant } A \ N \longrightarrow \neg \text{redundant } B \ N$ 
     $\longrightarrow \text{superposition}\text{-}rules \ A \ B \ C \longrightarrow \text{redundant } C \ N \vee C \in N)$ 
lemma
  assumes
    saturated: saturated  $N$  and
    finite: finite  $N$  and
    empty:  $\{\#\} \notin N$ 
  shows  $INTERP \ N \models_{hs} N$ 
proof (rule ccontr)
  let ?NI =  $INTERP \ N$ 
  assume  $\neg ?thesis$ 
  hence not-empty:  $\{E \in N. \neg ?N_I \models_h E\} \neq \{\}$ 
    unfolding true-clss-def Ball-def by auto
  def D  $\equiv \text{Min } \{E \in N. \neg ?N_I \models_h E\}$ 
  have [simp]:  $D \in N$ 
    unfolding D-def
    by (metis (mono-tags, lifting) Min-in not-empty finite mem-Collect-eq rev-finite-subset subsetI)
  have not-d-interp:  $\neg ?N_I \models_h D$ 
    unfolding D-def
    by (metis (mono-tags, lifting) Min-in finite mem-Collect-eq not-empty rev-finite-subset subsetI)
  have cls-not-D:  $\bigwedge E. \ E \in N \Longrightarrow E \neq D \Longrightarrow \neg ?N_I \models_h E \Longrightarrow D \leq E$ 
    using finite D-def by (auto simp del: less-eq-multiset)

```

```

obtain  $C\ L$  where  $D: D = C + \{\#L\# \}$  and  $LSD: L \in\# S\ D \vee (S\ D = \{\#\} \wedge \text{Max}(\text{set-mset } D) = L)$ 
proof (cases  $S\ D = \{\#\}$ )
  case False
  then obtain  $L$  where  $L \in\# S\ D$ 
    using Max-in-lits by blast
  moreover
    hence  $L \in\# D$ 
    using S-selects-subseteq[of D] by auto
    hence  $D = (D - \{\#L\# \}) + \{\#L\# \}$ 
    by auto
  ultimately show ?thesis using that by blast
next
let  $?L = \text{MMax } D$ 
case True
moreover
  have  $?L \in\# D$ 
    by (metis (no-types, lifting) Max-in-lits  $\langle D \in N \rangle$  empty)
  hence  $D = (D - \{\#?L\# \}) + \{\#?L\# \}$ 
  by auto
  ultimately show ?thesis using that by blast
qed
have red:  $\neg \text{redundant } D\ N$ 
proof (rule ccontr)
  assume red[simplified]:  $\sim\sim \text{redundant } D\ N$ 
  have  $\forall E < D. E \in N \longrightarrow ?N_{\mathcal{I}} \models_h E$ 
    using cls-not-D not-le by fastforce
  hence  $?N_{\mathcal{I}} \models_{hs} \text{clss-lt } N\ D$ 
  unfolding clss-lt-def true-clss-def Ball-def by blast
  thus False
  using red not-d-interp unfolding abstract-red-def redundant-iff-abstract
  using herbrand-true-clss-true-clss-cls-herbrand-true-clss by fast
qed

consider
  ( $L$ )  $P$  where  $L = \text{Pos } P$  and  $S\ D = \{\#\}$  and  $\text{Max}(\text{set-mset } D) = \text{Pos } P$ 
| ( $Lneg$ )  $P$  where  $L = \text{Neg } P$ 
using LSD S-selects-neg-lits[of D L] by (cases L) auto
thus False
proof cases
  case  $L$  note  $P = \text{this}(1)$  and  $S = \text{this}(2)$  and  $\text{max} = \text{this}(3)$ 
  have count  $D\ L > 1$ 
  proof (rule ccontr)
    assume  $\sim ?thesis$ 
    hence count: count  $D\ L = 1$ 
    unfolding  $D$  by auto
    have  $\neg ?N_{\mathcal{I}} \models_h D$ 
    using not-d-interp true-interp-imp-INTERP ground-resolution-with-selection-axioms
    by blast
  hence produces  $N\ D\ P$ 
  using not-empty empty finite  $\langle D \in N \rangle$  count L
    true-interp-imp-INTERP unfolding production-iff-produces unfolding production-unfold
    by (auto simp add: max not-empty)
  hence INTERP  $N \models_h D$ 
  unfolding  $D$ 

```


by (metis pos-literal-in-imp-true-cls produces-imp-Pos-in-lits
 production-subseteq-INTERP singletonI subsetCE)
 thus False
 using not-d-interp by blast
 qed
 then obtain C' where $C':D = C' + \{\#Pos P\# \} + \{\#Pos P\# \}$
 unfolding D by (metis P add.left-neutral add-less-cancel-right count-single count-union
 multi-member-split)
 have sup: superposition-rules $D D (D - \{\#L\# \})$
 unfolding $C' L$ by (auto simp add: superposition-rules.simps)
 have $C' + \{\#Pos P\# \} \# \subset \# C' + \{\#Pos P\# \} + \{\#Pos P\# \}$
 by auto
 moreover have $\neg ?N_{\mathcal{I}} \models h (D - \{\#L\# \})$
 using not-d-interp unfolding $C' L$ by auto
 ultimately have $C' + \{\#Pos P\# \} \notin N$
 by (metis (no-types, lifting) $C' P$ add-diff-cancel-right' cls-not-D less-multiset
 multi-self-add-other-not-self not-le)
 have $D - \{\#L\# \} \# \subset \# D$
 unfolding $C' L$ by auto
 have $c'-p-p: C' + \{\#Pos P\# \} + \{\#Pos P\# \} - \{\#Pos P\# \} = C' + \{\#Pos P\# \}$
 by auto
 have redundant $(C' + \{\#Pos P\# \}) N$
 using saturated red sup $\langle D \in N \rangle \langle C' + \{\#Pos P\# \} \notin N \rangle$ unfolding saturated-def $C' L c'-p-p$
 by blast
 moreover have $C' + \{\#Pos P\# \} \subseteq \# C' + \{\#Pos P\# \} + \{\#Pos P\# \}$
 by auto
 ultimately show False
 using red unfolding C' redundant-iff-abstract by (blast dest:
 abstract-red-subset-mset-abstract-red)
 next
 case Lneg note $L = this(1)$
 have $P \in ?N_{\mathcal{I}}$
 using not-d-interp unfolding D true-cls-def L by (auto split: split-if-asm)
 then obtain E where
 DPN: $E + \{\#Pos P\# \} \in N$ and
 prod: production $N (E + \{\#Pos P\# \}) = \{P\}$
 using in-interp-is-produced by blast
 have sup-EC: superposition-rules $(E + \{\#Pos P\# \}) (C + \{\#Neg P\# \}) (E + C)$
 using superposition-l by fast
 hence superposition $N (N \cup \{E+C\})$
 using DPN $\langle D \in N \rangle$ unfolding $D L$ by (auto simp add: superposition.simps)
 have
 PMax: $Pos P = MMax (E + \{\#Pos P\# \})$ and
 count $(E + \{\#Pos P\# \}) (Pos P) \leq 1$ and
 S $(E + \{\#Pos P\# \}) = \{\# \}$ and
 $\neg interp N (E + \{\#Pos P\# \}) \models h E + \{\#Pos P\# \}$
 using prod unfolding production-unfold by auto
 have $Neg P \notin \# E$
 using prod produces-imp-neg-notin-lits by force
 hence $\bigwedge y. y \in \# (E + \{\#Pos P\# \})$
 $\implies count (E + \{\#Pos P\# \}) (Neg P) < count (C + \{\#Neg P\# \}) (Neg P)$
 by (auto split: split-if-asm)
 moreover have $\bigwedge y. y \in \# (E + \{\#Pos P\# \}) \implies y < Neg P$
 using PMax by (metis DPN Max-less-iff empty finite-set-mset mem-set-mset-iff pos-less-neg
 set-mset-eq-empty-iff)

moreover have $E + \{\#Pos\ P\# \} \neq C + \{\#Neg\ P\# \}$
using *prod produces-imp-neg-notin-lits* **by** *force*
ultimately have $E + \{\#Pos\ P\# \} \# \subset \# C + \{\#Neg\ P\# \}$
unfolding *less-multiset_{HO}* **by** (*metis add.left-neutral add-lessD1*)
have *ce-lt-d*: $C + E \# \subset \# D$
unfolding $D\ L$
by (*metis (mono-tags, lifting) Max-pos-neg-less-multiset One-nat-def PMax count-single less-multiset-plus-right-nonempty mult-less-trans single-not-empty union-less-mono2 zero-less-Suc*)
have $?N_{\mathcal{I}} \models_h E + \{\#Pos\ P\# \}$
using $\langle P \in ?N_{\mathcal{I}} \rangle$ **by** *blast*
have $?N_{\mathcal{I}} \models_h C + E \vee C + E \notin N$
using *ce-lt-d cls-not-D* **unfolding** $D\text{-def}$ **by** *fastforce*
have $Pos\ P \notin \# C + E$
using $D\ \langle P \in \text{ground-resolution-with-selection.INTERP}\ S\ N \rangle$
 $\langle \text{count}\ (E + \{\#Pos\ P\# \})\ (Pos\ P) \leq 1 \rangle$ *multi-member-skip not-d-interp* **by** *auto*
hence $\bigwedge y. y \in \# C + E$
 $\implies \text{count}\ (C + E)\ (Pos\ P) < \text{count}\ (E + \{\#Pos\ P\# \})\ (Pos\ P)$
by (*auto split: split-if-asm*)

have $\neg \text{redundant}\ (C + E)\ N$
proof (*rule ccontr*)
assume $\text{red}'[\text{simplified}]: \neg\ ?thesis$
have $\text{abs: cls-lt}\ N\ (C + E) \models_p C + E$
using *redundant-iff-abstract red'* **unfolding** *abstract-red-def* **by** *auto*
have $\text{cls-lt}\ N\ (C + E) \models_p E + \{\#Pos\ P\# \} \vee \text{cls-lt}\ N\ (C + E) \models_p C + \{\#Neg\ P\# \}$
proof *clarify*
assume $CP: \neg\ \text{cls-lt}\ N\ (C + E) \models_p C + \{\#Neg\ P\# \}$
{ fix I
assume
 $\text{total-over-m}\ I\ (\text{cls-lt}\ N\ (C + E) \cup \{E + \{\#Pos\ P\# \}\})$ **and**
 $\text{consistent-interp}\ I$ **and**
 $I \models_s \text{cls-lt}\ N\ (C + E)$
hence $I \models C + E$
using *abs sorry*
moreover have $\neg\ I \models C + \{\#Neg\ P\# \}$
using CP **unfolding** *true-cls-cls-def*
sorry
ultimately have $I \models E + \{\#Pos\ P\# \}$ **by** *auto*
}
then show $\text{cls-lt}\ N\ (C + E) \models_p E + \{\#Pos\ P\# \}$
unfolding *true-cls-cls-def* **by** *auto*
qed
moreover have $\text{cls-lt}\ N\ (C + E) \subseteq \text{cls-lt}\ N\ (C + \{\#Neg\ P\# \})$
using *ce-lt-d mult-less-trans* **unfolding** *cls-lt-def D L* **by** *force*
ultimately have $\text{redundant}\ (C + \{\#Neg\ P\# \})\ N \vee \text{cls-lt}\ N\ (C + E) \models_p E + \{\#Pos\ P\# \}$
unfolding *redundant-iff-abstract abstract-red-def* **using** *true-cls-cls-subset* **by** *blast*
show *False sorry*
qed
moreover have $\neg\ \text{redundant}\ (E + \{\#Pos\ P\# \})\ N$
sorry
ultimately have $CEN: C + E \in N$
using $\langle D \in N \rangle\ \langle E + \{\#Pos\ P\# \} \in N \rangle$ *saturated sup-EC red* **unfolding** *saturated-def D L*
by (*metis union-commute*)
have $CED: C + E \neq D$

```

    using D ce-lt-d by auto
  have interp:  $\neg \text{INTERP } N \models_h C + E$ 
  sorry
  show False
    using cls-not-D[OF CEN CED interp] ce-lt-d unfolding INTERP-def less-eq-multiset-def by
auto
  qed
qed

end

lemma tautology-is-redundant:
  assumes tautology C
  shows abstract-red C N
  using assms unfolding abstract-red-def true-clss-cls-def tautology-def by auto

lemma subsumed-is-redundant:
  assumes AB:  $A \subset\# B$ 
  and AN:  $A \in N$ 
  shows abstract-red B N
proof -
  have A  $\in$  clss-lt N B using AN AB unfolding clss-lt-def
    by (auto dest: less-eq-imp-le-multiset simp add: multiset-order.dual-order.order-iff-strict)
  thus ?thesis
    using AB unfolding abstract-red-def true-clss-cls-def Partial-Clausal-Logic.true-clss-def
    by blast
qed

inductive redundant :: 'a clause  $\Rightarrow$  'a clauses  $\Rightarrow$  bool where
  subsumption:  $A \in N \Longrightarrow A \subset\# B \Longrightarrow \text{redundant } B N$ 

lemma redundant-is-redundancy-criterion:
  fixes A :: 'a :: wellorder clause and N :: 'a :: wellorder clauses
  assumes redundant A N
  shows abstract-red A N
  using assms
proof (induction rule: redundant.induct)
  case (subsumption A B N)
  thus ?case
    using subsumed-is-redundant[of A N B] unfolding abstract-red-def clss-lt-def by auto
qed

lemma redundant-mono:
   $\text{redundant } A N \Longrightarrow A \subseteq\# B \Longrightarrow \text{redundant } B N$ 
  apply (induction rule: redundant.induct)
  by (meson subset-mset.less-le-trans subsumption)

locale truc=
  selection S for S :: nat clause  $\Rightarrow$  nat clause
begin

end

end
theory Weidenbach-Book

```

```
imports  
  Prop-Normalisation  
  
  Prop-Resolution  
  
  Prop-Superposition  
  
  CDCL-NOT DPLL-NOT DPLL-W-Implementation CDCL-W-Implementation CDCL-W-Incremental  
  CDCL-WNOT CDCL-Two-Watched-Literals  
  
begin  
  
end
```