

Formalisation of Ground Resolution and CDCL in Isabelle/HOL

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22 Implementation for 2 Watched-Literals 540

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*:

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

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*: $rtranclp r a b \iff (a = b \vee tranclp r a b)$

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

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

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

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

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

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

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  $z$  assms(1) step.hyps(1) step.premis(2) apply auto[1]
    using  $IH z$  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 $\text{no-step step } S \equiv (\forall S'. \neg \text{step } S S')$

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

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

```

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

```

```

lemma tranclp-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 tranclp-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*:

$R\ a\ b \implies full\ R\ b\ c \implies full1\ R\ a\ c$

unfolding *full-def full1-def* **by** *auto*

lemma *full-unfold*:

$full\ r\ S\ S' \longleftrightarrow ((S = S' \wedge no\text{-}step\ r\ S') \vee full1\ r\ S\ S')$

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  $\exists b. R^{**} a b \wedge \text{no-step } R b$ 
proof (rule ccontr)
  assume  $\neg ?thesis$ 
  then have  $H: \bigwedge b. \neg R^{**} a b \vee \neg \text{no-step } R b$ 
    by blast
  def  $F \equiv \text{rec-nat } a (\lambda i b. \text{SOME } c. R b c)$ 
  have [simp]:  $F 0 = a$ 
    unfolding  $F\text{-def}$  by auto
  have [simp]:  $\bigwedge i. F (\text{Suc } i) = (\text{SOME } b. R (F i) b)$ 
    using  $F\text{-def}$  by simp
  { fix i
    have  $\forall j < i. R (F j) (F (\text{Suc } j))$ 
      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  $R (F i) (\text{SOME } b. R (F i) b)$ 
          using  $H$  by (simp add: someI-ex)
        then have  $\forall j < \text{Suc } i. R (F j) (F (\text{Suc } j))$ 
          using  $H \text{ Suc}$  by (simp add: less-Suc-eq)
        then show ?case by fast
      qed
    }
  then have  $\forall j. R (F j) (F (\text{Suc } j))$  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  $\exists b. \text{full } R a b$ 
  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: $wf ?r = (\neg (\exists f. \forall i. (f (\text{Suc } i), f i) \in ?r)), \llbracket wf ?r; \bigwedge k. (?f (\text{Suc } k), ?f k) \notin ?r \implies ?thesis \rrbracket \implies ?thesis$

```

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) ∈ r}
    using assms by (metis inv-image-def wf-inv-image)

lemma wf-wf-if-measure':
  assumes wf r and H: (⋀ x y. P x ⟹ g x y ⟹ (f y, f x) ∈ r)
  shows wf {(y, x). P x ∧ g x y}
  proof -
    have wf {(b, a). (f b, f a) ∈ r} using assms(1) wf-if-measure-f by auto
    then have wf {(b, a). P a ∧ g a b ∧ (f b, f a) ∈ r}
      using wf-subset[of - {(b, a). P a ∧ g a b ∧ (f b, f a) ∈ r}] by auto
    moreover have {(b, a). P a ∧ g a b ∧ (f b, f a) ∈ r} ⊆ {(b, a). (f b, f a) ∈ r} by auto
    moreover have {(b, a). P a ∧ g a b ∧ (f b, f a) ∈ r} = {(b, a). P a ∧ g a b} using H by auto
    ultimately show ?thesis using wf-subset by simp
  qed

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

lemma wfP-if-measure2: fixes f :: 'a ⇒ nat
  shows (⋀ x y. P x y ⟹ g x y ⟹ f x < f y) ⟹ wf {(x, y). P x y ∧ 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-finite: ⋀ U. P U ⟹ U ∈ A and
    finite: finite A and
    wf: wf R and
    trans: trans R
  shows wf {(T, S). (P S ∧ P T) ∧ (T, S) ∈ lexord R}
  proof (rule wfP-if-measure2)
    fix T S
    assume P: P S ∧ P T and
    s-le-t: (T, S) ∈ lexord R
    let ?f = λS. {U. (U, S) ∈ lexord R ∧ P U ∧ P S}
    have ?f T ⊆ ?f S
      using s-le-t P lexord-trans trans by auto
    moreover have T ∈ ?f S
      using s-le-t P by auto
    moreover have T ∉ ?f T
      using s-le-t by (auto simp add: lexord-irreflexive local.wf)
    ultimately have {U. (U, T) ∈ lexord R ∧ P U ∧ P T} ⊂ {U. (U, S) ∈ lexord R ∧ P U ∧ P S}
      by auto
    moreover have finite {U. (U, S) ∈ lexord R ∧ P U ∧ 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  $x = (a, b)$  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  $P \circ (\lambda(a, b). (b, a))$ ] 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**

$\bigwedge n. (\forall m < Suc\ n. P\ m) \implies P\ (Suc\ n)$

shows $P\ n$

apply (*induction rule: nat-less-induct*)

by (*rename-tac n, 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]*:

$0 < (\text{if } P \text{ then } a \text{ else } (0::nat)) \longleftrightarrow P \wedge 0 < a$

by *auto*

Bounded function have not been defined in Isabelle.

definition *bounded* **where**

$\text{bounded } f \longleftrightarrow (\exists b. \forall n. f\ n \leq b)$

abbreviation *unbounded* :: $('a \Rightarrow 'b::ord) \Rightarrow bool$ **where**

$\text{unbounded } f \equiv \neg \text{bounded } f$

lemma *not-bounded-nat-exists-larger*:

fixes $f :: nat \Rightarrow nat$

assumes *unbound*: $\text{unbounded } f$

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 ≤ n₀*)

apply (*metis (mono-tags, lifting) Max-ge Un-insert-right {finite {f n | n. n ≤ n₀}*

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 | n. n ≤ n₀}*

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 $k :: nat$ **and** $f :: nat \Rightarrow nat$

assumes $k > 0$

```

shows bounded  $f \longleftrightarrow \text{bounded } (\lambda i. k * f i)$ 
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  $\bigwedge x. f x \leq \text{Max } \{f x | x. \text{True}\}$ 
    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 $\langle B = [Suc\ m + \text{length } A..<n] \rangle$ by *auto*
 qed

lemma *Max-n-upt*: $Max\ (insert\ 0\ \{Suc\ 0..<n\}) = n - Suc\ 0$
 proof (induct n)
 case 0
 then show $?case$ by *simp*
 next
 case (Suc n) note *IH* = *this*
 have i : $insert\ 0\ \{Suc\ 0..<Suc\ n\} = insert\ 0\ \{Suc\ 0..<n\} \cup \{n\}$ 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*:
 $[c, d] = ys\ @\ y\ \# \ ys' \longleftrightarrow (ys = [] \wedge y = c \wedge ys' = [d]) \vee (ys = [c] \wedge y = d \wedge ys' = [])$
 by (cases ys ; cases ys') *auto*

lemma *lexn2-conv*:
 $([a, b], [c, d]) \in \text{lexn}\ r\ 2 \longleftrightarrow (a, c) \in r \vee (a = c \wedge (b, d) \in r)$
 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 $'v\ \text{propo} =$
 $FT \mid FF \mid FVar\ 'v \mid FNot\ 'v\ \text{propo} \mid FAnd\ 'v\ \text{propo}\ 'v\ \text{propo} \mid FOr\ 'v\ \text{propo}\ 'v\ \text{propo}$

| *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* $\equiv \{CF\} \cup \{CT\} \cup \{CVar\ x \mid x. \text{True}\}$

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*[*case-names nullary binary unary*]:

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** (*cases c*) (*auto simp: 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** (*cases 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*) \Longrightarrow *wf-conn* *c* [] |

wf-conn-unary[simp]: *c* = *CNot* \Longrightarrow *wf-conn* *c* [*ψ*] |

wf-conn-binary[simp]: *c* \in *binary-connectives* \Longrightarrow *wf-conn* *c* (*ψ* # *ψ'* # [])

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**

($\bigwedge v. c = CT \Longrightarrow P []$) **and**

($\bigwedge v. c = CF \Longrightarrow P []$) **and**

($\bigwedge v. c = CVar\ v \Longrightarrow P []$) **and**

($\bigwedge \psi. c = CNot \Longrightarrow P [\psi]$) **and**

($\bigwedge \psi\ \psi'. c = COr \Longrightarrow P [\psi, \psi']$) **and**

($\bigwedge \psi\ \psi'. c = CAnd \Longrightarrow P [\psi, \psi']$) **and**

($\bigwedge \psi\ \psi'. c = CImp \Longrightarrow P [\psi, \psi']$) **and**

($\bigwedge \psi\ \psi'. c = CEq \Longrightarrow P [\psi, \psi']$)

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* \Longrightarrow *conn* *CT* *l* = *FT*

wf-conn *CF* *l* \Longrightarrow *conn* *CF* *l* = *FF*

wf-conn (*CVar* *x*) *l* \Longrightarrow *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* (*ξ* @ *φ* # *ξ'*) $\longleftrightarrow \xi = [] \wedge \xi' = []$

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* \Longrightarrow *conn* *c* *l* = *FT* $\longleftrightarrow (c = CT \wedge l = [])$

wf-conn *c* *l* \Longrightarrow *conn* *c* *l* = *FF* $\longleftrightarrow (c = CF \wedge l = [])$

wf-conn *c* *l* \Longrightarrow *conn* *c* *l* = *FVar* *x* $\longleftrightarrow (c = CVar\ x \wedge l = [])$

wf-conn *c* *l* \Longrightarrow *conn* *c* *l* = *FAnd* *a* *b* $\longleftrightarrow (c = CAnd \wedge l = a \# b \# [])$

wf-conn *c* *l* \Longrightarrow *conn* *c* *l* = *FOr* *a* *b* $\longleftrightarrow (c = COr \wedge l = a \# b \# [])$

wf-conn *c* *l* \Longrightarrow *conn* *c* *l* = *FEq* *a* *b* $\longleftrightarrow (c = CEq \wedge l = a \# b \# [])$

wf-conn *c* *l* \Longrightarrow *conn* *c* *l* = *FImp* *a* *b* $\longleftrightarrow (c = CImp \wedge l = a \# b \# [])$

wf-conn *c* *l* \Longrightarrow *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 (rename-tac l, 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  $\in$  binary-connectives
  shows length l = 2  $\longleftrightarrow$  wf-conn c l
proof
  assume length l = 2
  thus wf-conn c l using wf-conn-binary list-length2-decomp using conn by metis
next
  assume wf-conn c l
  thus 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 propo
  case wf-conn-unary
  thus ?P [ $\psi$ ] using conn binary-connectives-def
    using connective.distinct by blast
  next
  fix  $\psi$   $\psi'$  :: 'v propo
  show ?P [ $\psi$ ,  $\psi'$ ] by auto
  qed
qed

```

```

lemma wf-conn-not-list-length[iff]:
  fixes l :: 'v propo list
  shows wf-conn CNot l  $\longleftrightarrow$  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 propo list and a :: 'v
  assumes corr: 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:
  length l = length l'  $\implies$  wf-conn c l  $\longleftrightarrow$  wf-conn c l'
proof -
  {
    fix l l'
    have length l = length l'  $\implies$  wf-conn c l  $\implies$  wf-conn c l'
    apply (cases c l rule: wf-conn.induct, auto)
  }

```

```

    by (metis wf-conn-bin-list-length)
  }
  thus length l = length l'  $\implies$  wf-conn c l = wf-conn c l' by metis
qed

```

```

lemma wf-conn-no-arity-change-helper:
  length (ξ @ φ # ξ') = length (ξ @ φ' # ξ')
  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 ψ
  shows c = CNot and l = [ψ]
  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 ψs :: 'v propo list
  assumes corr: wf-conn ca l
  and corr': wf-conn c ψs
  and eq: conn ca l = conn c ψs
  shows ca = c ∧ ψs = l
  using corr
proof (cases ca l rule: wf-conn.cases)
  case (wf-conn-nullary v)
  thus ca = c ∧ ψs = l using assms
    by (metis conn.simps(1) conn.simps(2) conn.simps(3) wf-conn-list(1-3))
next
  case (wf-conn-unary ψ')
  hence *: FNot ψ' = conn c ψs using conn-inj-not eq assms by auto
  hence c = ca by (metis conn-inj-not(1) corr' wf-conn-unary(2))
  moreover have ψs = l using * conn-inj-not(2) corr' wf-conn-unary(1) by force
  ultimately show ca = c ∧ ψs = l by auto
next
  case (wf-conn-binary ψ' ψ'')
  thus ca = c ∧ ψs = l
    using eq corr' unfolding binary-connectives-def apply (cases 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]: φ  $\preceq$  φ |
  subformula-into-subformula: ψ ∈ set l  $\implies$  wf-conn c l  $\implies$  φ  $\preceq$  ψ  $\implies$  φ  $\preceq$  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 $b: FNot\ \varphi \preceq \psi \implies \varphi \preceq \psi$

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 ∈ binary-connectives*

shows $f \preceq conn\ c\ [f, g]$

and $g \preceq conn\ c\ [f, g]$

proof $-$

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

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

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

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

next

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

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

ultimately show $g \preceq conn\ c\ [f, g]$ **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 $\varphi\ \psi :: 'v\ propo$

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 $\varphi \preceq conn\ c\ l$

and *wf-conn c l*

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

shows $\varphi = conn\ c\ l$

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

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

lemma *wf-subformula-conn-cases*:

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

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  $\varphi \preceq conn CAnd [\psi, \psi'] \longleftrightarrow (\varphi = conn CAnd [\psi, \psi'] \vee (\exists \psi''. \psi'' \in set [\psi, \psi'] \wedge \varphi \preceq \psi''))$ 
    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  $\varphi \preceq conn COr [\psi, \psi'] \longleftrightarrow (\varphi = conn COr [\psi, \psi'] \vee (\exists \psi''. \psi'' \in set [\psi, \psi'] \wedge \varphi \preceq \psi''))$ 
    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  $\varphi \preceq conn CEq [\psi, \psi'] \longleftrightarrow (\varphi = conn CEq [\psi, \psi'] \vee (\exists \psi''. \psi'' \in set [\psi, \psi'] \wedge \varphi \preceq \psi''))$ 
    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  $\varphi \preceq conn CImp [\psi, \psi'] \longleftrightarrow (\varphi = conn CImp [\psi, \psi'] \vee (\exists \psi''. \psi'' \in set [\psi, \psi'] \wedge \varphi \preceq \psi''))$ 
    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*: $\exists c l. \varphi = conn c l \wedge wf-conn c l$
by (*cases* φ) *force+*

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

```

assumes wf: wf-conn c l
shows  $\varphi \preceq conn c l \longleftrightarrow (\varphi = conn c l \vee (\exists \psi \in set l. \varphi \preceq \psi))$  (is  $?A \longleftrightarrow ?B$ )

```

proof (*rule iffI*)

```

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

```

```

moreover assume  $?A$ 
ultimately show  $?B$  using wf by metis

```

next

```

assume  $?B$ 
then show  $\varphi \preceq conn c l$  using wf 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* $\varphi\ \psi$) = *vars-of-prop* $\varphi \cup$ *vars-of-prop* ψ |
vars-of-prop (*FOr* $\varphi\ \psi$) = *vars-of-prop* $\varphi \cup$ *vars-of-prop* ψ |
vars-of-prop (*FImp* $\varphi\ \psi$) = *vars-of-prop* $\varphi \cup$ *vars-of-prop* ψ |
vars-of-prop (*FEq* $\varphi\ \psi$) = *vars-of-prop* $\varphi \cup$ *vars-of-prop* ψ

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

fixes $\xi\ \xi' :: 'v\ \text{propo}\ \text{list}$ **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* $\psi \subseteq$ *vars-of-prop* (*conn* *c* *l*)

proof (*cases c* *rule: connective-cases-arity-2*)

case *nullary*

hence *False* **using** *corr* *incl* **by** *auto*

thus *vars-of-prop* $\psi \subseteq$ *vars-of-prop* (*conn* *c* *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* $\psi \subseteq$ *vars-of-prop* (*conn* *c* *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* $\psi \subseteq$ *vars-of-prop* (*conn* *c* *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) = {[]} |
pos (FAnd  $\varphi$   $\psi$ ) = {[]}  $\cup$  { L # p | p. p  $\in$  pos  $\varphi$  }  $\cup$  { R # p | p. p  $\in$  pos  $\psi$  } |
pos (FOr  $\varphi$   $\psi$ ) = {[]}  $\cup$  { L # p | p. p  $\in$  pos  $\varphi$  }  $\cup$  { R # p | p. p  $\in$  pos  $\psi$  } |
pos (FEq  $\varphi$   $\psi$ ) = {[]}  $\cup$  { L # p | p. p  $\in$  pos  $\varphi$  }  $\cup$  { R # p | p. p  $\in$  pos  $\psi$  } |
pos (FImp  $\varphi$   $\psi$ ) = {[]}  $\cup$  { L # p | p. p  $\in$  pos  $\varphi$  }  $\cup$  { R # p | p. p  $\in$  pos  $\psi$  } |
pos (FNot  $\varphi$ ) = {[]}  $\cup$  { L # p | p. p  $\in$  pos  $\varphi$  }

```

```

lemma finite-pos: finite (pos  $\varphi$ )
by (induct  $\varphi$ , auto)

```

```

lemma finite-inj-comp-set:
fixes s :: 'v set
assumes finite: finite s
and inj: inj f
shows card ({f p | p. p  $\in$  s}) = card s
using finite
proof (induct s rule: finite-induct)
show card {f p | p. p  $\in$  {}} = card {} by auto
next
fix x :: 'v and s:: 'v set
assume f: finite s and notin: x  $\notin$  s
and IH: card {f p | p. p  $\in$  s} = card s
have f': finite {f p | p. p  $\in$  insert x s} using f by auto
have notin': f x  $\notin$  {f p | p. p  $\in$  s} using notin inj injD by fastforce
have {f p | p. p  $\in$  insert x s} = insert (f x) {f p | p. p  $\in$  s} by auto
hence card {f p | p. p  $\in$  insert x s} = 1 + card {f p | p. p  $\in$  s}
using finite card-insert-disjoint f' notin' by auto
moreover have ... = card (insert x s) using notin f IH by auto
finally show card {f p | p. p  $\in$  insert x s} = card (insert x s) .
qed

```

```

lemma cons-inject:
inj (op # s)
by (meson injI list.inject)

```

```

lemma finite-insert-nil-cons:
finite s  $\implies$  card (insert [] {L # p | p. p  $\in$  s}) = 1 + card {L # p | p. p  $\in$  s}
using card-insert-disjoint by auto

```

```

lemma card-not[simp]:
card (pos (FNot  $\varphi$ )) = 1 + card (pos  $\varphi$ )
by (simp add: cons-inject finite-inj-comp-set finite-pos)

```

```

lemma card-seperate:
assumes finite s1 and finite s2
shows card ({L # p | p. p  $\in$  s1}  $\cup$  {R # p | p. p  $\in$  s2}) = card ({L # p | p. p  $\in$  s1})
+ card({R # p | p. p  $\in$  s2}) (is card (?L $\cup$ ?R) = card ?L + card ?R)
proof -

```

```

have finite ?L using assms by auto
moreover have finite ?R using assms by auto
moreover have ?L ∩ ?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 $\varphi1 \ \varphi2 :: 'v \text{ propo}$

assume *IH1*: $\text{card } (\text{vars-of-prop } \varphi1) \leq \text{card } (\text{pos } \varphi1)$

and *IH2*: $\text{card } (\text{vars-of-prop } \varphi2) \leq \text{card } (\text{pos } \varphi2)$

let $?L = \{L \# p \mid p. p \in \text{pos } \varphi1\}$

let $?R = \{R \# p \mid p. p \in \text{pos } \varphi2\}$

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

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

moreover **have** $\dots = \text{card } (\text{pos } \varphi1) + \text{card } (\text{pos } \varphi2)$

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

moreover **have** $\dots \geq \text{card } (\text{vars-of-prop } \varphi1) + \text{card } (\text{vars-of-prop } \varphi2)$ **using** *IH1 IH2* **by** *arith*

hence $\dots \geq \text{card } (\text{vars-of-prop } \varphi1 \cup \text{vars-of-prop } \varphi2)$ **using** *card-Un-le le-trans* **by** *blast*

ultimately

show $\text{card } (\text{vars-of-prop } \varphi1 \cup \text{vars-of-prop } \varphi2) \leq \text{Suc } (\text{card } (?L \cup ?R))$

$\text{card } (\text{vars-of-prop } \varphi1 \cup \text{vars-of-prop } \varphi2) \leq \text{Suc } (\text{card } (?L \cup ?R))$

$\text{card } (\text{vars-of-prop } \varphi1 \cup \text{vars-of-prop } \varphi2) \leq \text{Suc } (\text{card } (?L \cup ?R))$

$\text{card } (\text{vars-of-prop } \varphi1 \cup \text{vars-of-prop } \varphi2) \leq \text{Suc } (\text{card } (?L \cup ?R))$

by *auto*

qed

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

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

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

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

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

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

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

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 $p \ \varphi \ \varphi' \implies \varphi' \preceq \varphi$

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  $\varphi' \preceq \varphi \implies \exists p. \text{path-to } p \varphi \varphi'$ 
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  $\psi$  wf-conn-Not-decomp by fastforce
    hence path-to ( $L \# p$ ) ( $\text{conn } c \ l$ )  $\varphi'$  by (metis c wf-conn-unary p 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 wf-conn-bin-list-length
      list-length2-decomp by metis
    hence  $a = \psi \vee b = \psi$  using  $\psi$  by auto
    hence path-to ( $L \# p$ ) ( $\text{conn } c \ l$ )  $\varphi' \vee \text{path-to } (R \# p) (\text{conn } c \ l) \varphi'$  using c 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 ( $L \# l$ ) ( $FAnd \ \varphi \ \varphi'$ )  $\psi = FAnd \ (\text{replace-at } l \ \varphi \ \psi) \ \varphi'$  |
  replace-at ( $R \# l$ ) ( $FAnd \ \varphi \ \varphi'$ )  $\psi = FAnd \ \varphi \ (\text{replace-at } l \ \varphi' \ \psi)$  |
  replace-at ( $L \# l$ ) ( $FOr \ \varphi \ \varphi'$ )  $\psi = FOr \ (\text{replace-at } l \ \varphi \ \psi) \ \varphi'$  |
  replace-at ( $R \# l$ ) ( $FOr \ \varphi \ \varphi'$ )  $\psi = FOr \ \varphi \ (\text{replace-at } l \ \varphi' \ \psi)$  |
  replace-at ( $L \# l$ ) ( $FEq \ \varphi \ \varphi'$ )  $\psi = FEq \ (\text{replace-at } l \ \varphi \ \psi) \ \varphi'$  |
  replace-at ( $R \# l$ ) ( $FEq \ \varphi \ \varphi'$ )  $\psi = FEq \ \varphi \ (\text{replace-at } l \ \varphi' \ \psi)$  |
  replace-at ( $L \# l$ ) ( $FImp \ \varphi \ \varphi'$ )  $\psi = FImp \ (\text{replace-at } l \ \varphi \ \psi) \ \varphi'$  |
  replace-at ( $R \# l$ ) ( $FImp \ \varphi \ \varphi'$ )  $\psi = FImp \ \varphi \ (\text{replace-at } l \ \varphi' \ \psi)$  |
  replace-at ( $L \# l$ ) ( $FNot \ \varphi$ )  $\psi = FNot \ (\text{replace-at } l \ \varphi \ \psi)$ 

```

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
 $\mathcal{A} \models FT = \text{True}$  |
 $\mathcal{A} \models FF = \text{False}$  |
 $\mathcal{A} \models FVar \ v = (\mathcal{A} \ v)$  |

```


$\mathcal{A} \models FNot \varphi = (\neg(\mathcal{A} \models \varphi)) \mid$
 $\mathcal{A} \models FAnd \varphi_1 \varphi_2 = (\mathcal{A} \models \varphi_1 \wedge \mathcal{A} \models \varphi_2) \mid$
 $\mathcal{A} \models FOr \varphi_1 \varphi_2 = (\mathcal{A} \models \varphi_1 \vee \mathcal{A} \models \varphi_2) \mid$
 $\mathcal{A} \models FImp \varphi_1 \varphi_2 = (\mathcal{A} \models \varphi_1 \longrightarrow \mathcal{A} \models \varphi_2) \mid$
 $\mathcal{A} \models FEq \varphi_1 \varphi_2 = (\mathcal{A} \models \varphi_1 \longleftrightarrow \mathcal{A} \models \varphi_2)$

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 $'v$ *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* φ)

shows $A \models \varphi \longleftrightarrow B \models \varphi$

using *assms* **unfolding** *same-over-set-def* **by** (*induct* φ , *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* :: $('v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}) \Rightarrow 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$

for $r :: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **where**

global-rel: $r \varphi \psi \Longrightarrow \text{propo-rew-step } r \varphi \psi$ |

propo-rew-one-step-lift: $\text{propo-rew-step } r \varphi \varphi' \Longrightarrow \text{wf-conn } c (\psi s @ \varphi \# \psi s')$

$\Longrightarrow \text{propo-rew-step } r (\text{conn } c (\psi s @ \varphi \# \psi s')) (\text{conn } c (\psi s @ \varphi' \# \psi s'))$

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 $\text{propo-rew-step } r \varphi \varphi' \Longrightarrow \exists \psi \psi'. \psi \preceq \varphi \wedge \psi' \preceq \varphi' \wedge r \psi \psi'$

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 ψ' .

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

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

shows $\psi \preceq \varphi \Longrightarrow r \psi \psi' \Longrightarrow (\exists \varphi'. \psi' \preceq \varphi' \wedge \text{propo-rew-step } r \varphi \varphi')$

proof (*induct* φ *rule*: *subformula.induct*)

case *subformula-refl*

hence $\text{propo-rew-step } r \psi \psi'$ **using** *propo-rew-step.intros* **by** *auto*

moreover **have** $\psi' \preceq \psi'$ **using** *Prop-Logic.subformula-refl* **by** *auto*

ultimately show $\exists \varphi'. \psi' \preceq \varphi' \wedge \text{propo-rew-step } r \varphi \varphi'$ **by** *fastforce*

next

case (subformula-into-subformula ψ'' 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 φ' where $*$: $\psi' \preceq \varphi' \wedge \text{propo-rew-step } r \ \psi'' \ \varphi'$ by *metis*
 moreover obtain $\xi \ \xi' :: 'v \ \text{propo list}$ where
 $l: l = \xi @ \psi'' \# \xi'$ using *List.split-list* ψ'' by *metis*
 ultimately have $\text{propo-rew-step } r \ (\text{conn } c \ l) \ (\text{conn } c \ (\xi @ \varphi' \# \xi'))$
 using *propo-rew-step.intros(2)* wf by *metis*
 moreover have $\psi' \preceq \text{conn } c \ (\xi @ \varphi' \# \xi')$
 using $wf * wf\text{-conn-no-arity-change}$ *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 $wf: wf\text{-conn } c \ l$ and $wf': wf\text{-conn } c \ l'$
 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** $IH: r \psi \psi' \wedge path\text{-}to\ p\ \varphi \psi \wedge replace\text{-}at\ p\ \varphi \psi' = \varphi'$ **using** $IH0$ **by** *metis*

```

{
  fix x :: 'v
  assume c = CT  $\vee$  c = CF  $\vee$  c = CVar x
  hence False using corr by auto
  hence  $\exists \psi \psi' p. r \psi \psi' \wedge path\text{-}to\ p\ (conn\ c\ (\xi @ (\varphi \# \xi'))) \psi$ 
     $\wedge replace\text{-}at\ p\ (conn\ c\ (\xi @ (\varphi \# \xi'))) \psi' = conn\ c\ (\xi @ (\varphi' \# \xi'))$ 
    by fast
}
moreover {
  assume c: c = CNot
  hence empty:  $\xi = [] \ \xi' = []$  using corr by auto
  have path-to (L#p) (conn c ( $\xi @ (\varphi \# \xi')$ ))  $\psi$ 
    using c empty IH wf-conn-unary path-to-l by fastforce
  moreover have replace-at (L#p) (conn c ( $\xi @ (\varphi \# \xi')$ ))  $\psi' = conn\ c\ (\xi @ (\varphi' \# \xi'))$ 
    using c empty IH by auto
  ultimately have  $\exists \psi \psi' p. r \psi \psi' \wedge path\text{-}to\ p\ (conn\ c\ (\xi @ (\varphi \# \xi'))) \psi$ 
     $\wedge replace\text{-}at\ p\ (conn\ c\ (\xi @ (\varphi \# \xi'))) \psi' = conn\ c\ (\xi @ (\varphi' \# \xi'))$ 
    using IH by metis
}
moreover {
  assume c: c  $\in$  binary-connectives
  have length ( $\xi @ \varphi \# \xi'$ ) = 2 using wf-conn-bin-list-length corr c by metis
  hence length  $\xi$  + length  $\xi' = 1$  by auto
  hence ld: (length  $\xi = 1 \wedge length\ \xi' = 0$ )  $\vee$  (length  $\xi = 0 \wedge length\ \xi' = 1$ ) by arith
  obtain a b where ab: ( $\xi = [] \wedge \xi' = [b]$ )  $\vee$  ( $\xi = [a] \wedge \xi' = []$ )
    using ld by (case-tac  $\xi$ , case-tac  $\xi'$ , auto)
  {
    assume  $\varphi: \xi = [] \wedge \xi' = [b]$ 
    have path-to (L#p) (conn c ( $\xi @ (\varphi \# \xi')$ ))  $\psi$ 
      using  $\varphi$  c IH ab corr by (simp add: path-to-l)
    moreover have replace-at (L#p) (conn c ( $\xi @ (\varphi \# \xi')$ ))  $\psi' = conn\ c\ (\xi @ (\varphi' \# \xi'))$ 
      using c IH ab  $\varphi$  unfolding binary-connectives-def by auto
    ultimately have  $\exists \psi \psi' p. r \psi \psi' \wedge path\text{-}to\ p\ (conn\ c\ (\xi @ (\varphi \# \xi'))) \psi$ 
       $\wedge replace\text{-}at\ p\ (conn\ c\ (\xi @ (\varphi \# \xi'))) \psi' = conn\ c\ (\xi @ (\varphi' \# \xi'))$ 
      using IH by metis
  }
  moreover {
    assume  $\varphi: \xi = [a] \ \xi' = []$ 
    hence path-to (R#p) (conn c ( $\xi @ (\varphi \# \xi')$ ))  $\psi$ 
      using c IH corr path-to-r corr  $\varphi$  by (simp add: path-to-r)
    moreover have replace-at (R#p) (conn c ( $\xi @ (\varphi \# \xi')$ ))  $\psi' = conn\ c\ (\xi @ (\varphi' \# \xi'))$ 
      using c IH ab  $\varphi$  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-neg*)

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*:
 $\text{full } (\text{propo-rew-step } r) \varphi' \varphi \implies \neg(\exists \psi \psi'. \psi \preceq \varphi \wedge r \psi \psi')$
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* :: $('a \text{ propo} \Rightarrow \text{bool}) \Rightarrow 'a \text{ propo} \Rightarrow \text{bool}$ **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]:
 $\text{test-symb } FT \implies \text{all-subformula-st test-symb } FT$
 $\text{test-symb } FF \implies \text{all-subformula-st test-symb } FF$
 $\text{test-symb } (FVar \ x) \implies \text{all-subformula-st test-symb } (FVar \ x)$
unfolding *all-subformula-st-def* **using** *subformula-leaf* **by** *metis+*

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

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

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

lemma *helper-fact*: $c \in \text{binary-connectives} \longleftrightarrow (c = COr \vee c = CAnd \vee c = CEq \vee c = CImp)$

unfolding *binary-connectives-def* **by** *auto*

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

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

shows $\text{all-subformula-st test-symb } (FAnd \ \varphi \ \psi)$

$\longleftrightarrow (test_symb (FAnd \varphi \psi) \wedge all_subformula_st \ test_symb \varphi \wedge all_subformula_st \ test_symb \psi)$
and $all_subformula_st \ test_symb (FOr \varphi \psi)$
 $\longleftrightarrow (test_symb (FOr \varphi \psi) \wedge all_subformula_st \ test_symb \varphi \wedge all_subformula_st \ test_symb \psi)$
and $all_subformula_st \ test_symb (FNot \varphi)$
 $\longleftrightarrow (test_symb (FNot \varphi) \wedge all_subformula_st \ test_symb \varphi)$
and $all_subformula_st \ test_symb (FEq \varphi \psi)$
 $\longleftrightarrow (test_symb (FEq \varphi \psi) \wedge all_subformula_st \ test_symb \varphi \wedge all_subformula_st \ test_symb \psi)$
and $all_subformula_st \ test_symb (FImp \varphi \psi)$
 $\longleftrightarrow (test_symb (FImp \varphi \psi) \wedge all_subformula_st \ test_symb \varphi \wedge all_subformula_st \ test_symb \psi)$
proof –
have $all_subformula_st \ test_symb (FAnd \varphi \psi) \longleftrightarrow all_subformula_st \ test_symb (conn \ CAnd [\varphi, \psi])$
by *auto*
moreover have $\dots \longleftrightarrow test_symb (conn \ CAnd [\varphi, \psi]) \wedge (\forall \xi \in set [\varphi, \psi]. all_subformula_st \ test_symb \xi)$
using $all_subformula_st_decomp \ wf_conn_helper_facts(5)$ **by** *metis*
finally show $all_subformula_st \ test_symb (FAnd \varphi \psi)$
 $\longleftrightarrow (test_symb (FAnd \varphi \psi) \wedge all_subformula_st \ test_symb \varphi \wedge all_subformula_st \ test_symb \psi)$
by *simp*

have $all_subformula_st \ test_symb (FOr \varphi \psi) \longleftrightarrow all_subformula_st \ test_symb (conn \ COr [\varphi, \psi])$
by *auto*
moreover have $\dots \longleftrightarrow$
 $(test_symb (conn \ COr [\varphi, \psi]) \wedge (\forall \xi \in set [\varphi, \psi]. all_subformula_st \ test_symb \xi))$
using $all_subformula_st_decomp \ wf_conn_helper_facts(6)$ **by** *metis*
finally show $all_subformula_st \ test_symb (FOr \varphi \psi)$
 $\longleftrightarrow (test_symb (FOr \varphi \psi) \wedge all_subformula_st \ test_symb \varphi \wedge all_subformula_st \ test_symb \psi)$
by *simp*

have $all_subformula_st \ test_symb (FEq \varphi \psi) \longleftrightarrow all_subformula_st \ test_symb (conn \ CEq [\varphi, \psi])$
by *auto*
moreover have \dots
 $\longleftrightarrow (test_symb (conn \ CEq [\varphi, \psi]) \wedge (\forall \xi \in set [\varphi, \psi]. all_subformula_st \ test_symb \xi))$
using $all_subformula_st_decomp \ wf_conn_helper_facts(8)$ **by** *metis*
finally show $all_subformula_st \ test_symb (FEq \varphi \psi)$
 $\longleftrightarrow (test_symb (FEq \varphi \psi) \wedge all_subformula_st \ test_symb \varphi \wedge all_subformula_st \ test_symb \psi)$
by *simp*

have $all_subformula_st \ test_symb (FImp \varphi \psi) \longleftrightarrow all_subformula_st \ test_symb (conn \ CImp [\varphi, \psi])$
by *auto*
moreover have \dots
 $\longleftrightarrow (test_symb (conn \ CImp [\varphi, \psi]) \wedge (\forall \xi \in set [\varphi, \psi]. all_subformula_st \ test_symb \xi))$
using $all_subformula_st_decomp \ wf_conn_helper_facts(7)$ **by** *metis*
finally show $all_subformula_st \ test_symb (FImp \varphi \psi)$
 $\longleftrightarrow (test_symb (FImp \varphi \psi) \wedge all_subformula_st \ test_symb \varphi \wedge all_subformula_st \ test_symb \psi)$
by *simp*

have $all_subformula_st \ test_symb (FNot \varphi) \longleftrightarrow all_subformula_st \ test_symb (conn \ CNot [\varphi])$
by *auto*
moreover have $\dots = (test_symb (conn \ CNot [\varphi]) \wedge (\forall \xi \in set [\varphi]. all_subformula_st \ test_symb \xi))$
using $all_subformula_st_decomp \ wf_conn_helper_facts(1)$ **by** *metis*
finally show $all_subformula_st \ test_symb (FNot \varphi)$
 $\longleftrightarrow (test_symb (FNot \varphi) \wedge all_subformula_st \ test_symb \varphi)$ **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 $r :: 'v \text{ propo} \Rightarrow 'v \text{ propo} \Rightarrow \text{bool}$ **and** $\text{test-symb} :: 'v \text{ propo} \Rightarrow \text{bool}$ **and** $x :: 'v$
and $\varphi :: 'v \text{ propo}$
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* φ *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* φ) **note** $IH = \text{this}(1)[OF\ \text{this}(2)]$ **and** $r = \text{this}(2)$ **and** $nst = \text{this}(3)$ **and** $\text{subf} = \text{this}(4)$
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 ψ **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) $nst\ \text{subf}$ **by** *blast*
hence $\exists \psi\ \psi'. \psi \preceq FNot\ \varphi \wedge r\ \psi\ \psi'$
using $H\ \text{subformula-in-subformula-not subformula-refl subformula-trans}$ **by** *blast*
}
ultimately **show** $\exists \psi\ \psi'. \psi \preceq FNot\ \varphi \wedge r\ \psi\ \psi'$ **by** *blast*
next
case (*binary* $\varphi\ \varphi1\ \varphi2$)
note $IH\ \varphi1-0 = \text{this}(1)[OF\ \text{this}(4)]$ **and** $IH\ \varphi2-0 = \text{this}(2)[OF\ \text{this}(4)]$ **and** $r = \text{this}(4)$
and $\varphi = \text{this}(3)$ **and** $le = \text{this}(5)$ **and** $nst = \text{this}(6)$

obtain $c :: 'v \text{ connective}$ **where**
 $c: (c = CAnd \vee c = COr \vee c = CImp \vee c = CEq) \wedge \text{conn } c\ [\varphi1, \varphi2] = \varphi$
using φ **by** *fastforce*

hence *corr*: $wf\text{-conn } c\ [\varphi1, \varphi2]$ **using** *wf-conn.simps unfolding binary-connectives-def* **by** *auto*
have *inc*: $\varphi1 \preceq \varphi \varphi2 \preceq \varphi$ **using** *binary-connectives-def* $c\ \text{subformula-in-binary-conn}$ **by** *blast+*
from $r\ IH\ \varphi1-0$ **have** $IH\ \varphi1: \neg \text{all-subformula-st test-symb } \varphi1 \implies \exists \psi\ \psi'. \psi \preceq \varphi1 \wedge r\ \psi\ \psi'$
using *inc*(1) *subformula-trans* le **by** *blast*
from $r\ IH\ \varphi2-0$ **have** $IH\ \varphi2: \neg \text{all-subformula-st test-symb } \varphi2 \implies \exists \psi. \psi \preceq \varphi2 \wedge (\exists \psi'. r\ \psi\ \psi')$
using *inc*(2) *subformula-trans* le **by** *blast*
have *cases*: $\neg \text{test-symb } \varphi \vee \neg \text{all-subformula-st test-symb } \varphi1 \vee \neg \text{all-subformula-st test-symb } \varphi2$


```

    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 propo  $\Rightarrow$  'v propo  $\Rightarrow$  bool and test-symb:: 'v propo  $\Rightarrow$  bool and x:: 'v
  and  $\varphi \psi \Phi$ :: 'v 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
  propo-rew-step r  $\varphi \psi$  and
   $\varphi \preceq \Phi$  and
  all-subformula-st test-symb  $\varphi$ 
  shows 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 rel = this(1) and  $\varphi = \text{this}(2)$  and corr = this(3) and  $\Phi = \text{this}(4)$  and nst = this(5)
  have sq:  $\varphi \preceq \Phi$ 
    using  $\Phi$  corr subformula-into-subformula subformula-refl subformula-trans
    by (metis in-set-conv-decomp)
  from corr have  $\forall \psi. \psi \in \text{set } (\xi @ \varphi \# \xi') \longrightarrow \text{all-subformula-st test-symb } \psi$ 
    using 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  $\varphi$  sq by fastforce
  hence test-symb  $\varphi'$  using all-subformula-st-test-symb-true-phi by auto
  moreover from corr nst have test-symb (conn c ( $\xi @ \varphi \# \xi'$ ))

```

```

    using all-subformula-st-decomp by blast
ultimately have test-symb: test-symb (conn c (ξ @ φ' # ξ')) using H' sq corr rel by blast

have wf-conn c (ξ @ φ' # ξ')
  by (metis wf-conn-no-arity-change-helper corr wf-conn-no-arity-change)
thus all-subformula-st test-symb (conn c (ξ @ φ' # ξ'))
  using * 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 propo ⇒ 'v propo ⇒ bool and test-symb:: 'v propo ⇒ bool and x :: 'v
  and φ ψ :: 'v propo
  assumes
    H: ∀ φ' ψ. r φ' ψ ⟶ all-subformula-st test-symb φ' ⟶ all-subformula-st test-symb ψ and
    H': ∀ (c:: 'v connective) ξ φ ξ' φ'. wf-conn c (ξ @ φ # ξ') ⟶ test-symb (conn c (ξ @ φ # ξ'))
      ⟶ test-symb φ' ⟶ test-symb (conn c (ξ @ φ' # ξ')) and
    propo-rew-step r φ ψ and
    all-subformula-st test-symb φ
  shows all-subformula-st test-symb ψ
  using propo-rew-step-inv-stay'[of φ r test-symb φ ψ] 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 propo ⇒ 'v propo ⇒ bool and test-symb:: 'v propo ⇒ bool and x :: 'v
  and φ ψ :: 'v propo
  assumes
    H: ∀ φ ψ. propo-rew-step r φ ψ ⟶ all-subformula-st test-symb φ
      ⟶ all-subformula-st test-symb ψ and
    H': ∀ (c:: 'v connective) ξ φ ξ' φ'. φ ⪯ Φ ⟶ propo-rew-step r φ φ'
      ⟶ wf-conn c (ξ @ φ # ξ') ⟶ test-symb (conn c (ξ @ φ # ξ')) ⟶ test-symb φ'
      ⟶ test-symb (conn c (ξ @ φ' # ξ')) and
    φ ⪯ Φ and
    full: full (propo-rew-step r) φ ψ and
    init: all-subformula-st test-symb φ
  shows all-subformula-st test-symb ψ
  using assms unfolding full-def
proof -
  have rel: (propo-rew-step r)** φ ψ
    using full unfolding full-def by auto
  thus all-subformula-st test-symb ψ
    using init
  proof (induct rule: rtranclp-induct)
    case base
    then show 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)
    then have all-subformula-st test-symb b by metis
    then show all-subformula-st test-symb c using propo-rew-step-inv-stay' H H' 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**

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

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

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

using *full-propo-rew-step-inv-stay-with-inc*[of r $\text{test-symb } \varphi$] *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** $\text{test-symb} :: 'v \text{ propo} \Rightarrow \text{bool}$ **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**

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

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

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

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*

thus $\text{all-subformula-st test-symb } \varphi$ **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** $\text{all} = \text{this}(4)$

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

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

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** $\text{test-symb} :: 'v \text{ propo} \Rightarrow \text{bool}$ **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**

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

$\longrightarrow (\text{test-symb } (\text{conn } c l) \longleftrightarrow \text{test-symb } (\text{conn } c l'))$ **and**

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

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

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

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  $\psi$ 
    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  $\varphi$   $\psi$ ) (FAnd (FImp  $\varphi$   $\psi$ ) (FImp  $\psi$   $\varphi$ ))

```

```

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-consistant:
  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 connective and l :: 'v propo list
  assumes wf: wf-conn c l
  shows no-equiv-symb (conn c l)  $\longleftrightarrow$  c  $\neq$  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

$\neg \text{no-equiv } (FEq \ \varphi \ \psi)$

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

no-equiv (*FNot* φ) \longleftrightarrow *no-equiv* φ

no-equiv (*FAnd* $\varphi \ \psi$) \longleftrightarrow (*no-equiv* $\varphi \wedge$ *no-equiv* ψ)

no-equiv (*FOR* $\varphi \ \psi$) \longleftrightarrow (*no-equiv* $\varphi \wedge$ *no-equiv* ψ)

no-equiv (*FImp* $\varphi \ \psi$) \longleftrightarrow (*no-equiv* $\varphi \wedge$ *no-equiv* ψ)

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*: *elim-equiv* (*conn* *c* *l*) ψ

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

}

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

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 propo \Rightarrow 'v propo \Rightarrow bool **where**
[simp]: *elim-imp* (*FImp* φ ψ) (*FOr* (*FNot* φ) ψ)

lemma *elim-imp-transformation-consistent*:
 $A \models \text{FImp } \varphi \ \psi \longleftrightarrow A \models \text{FOr } (\text{FNot } \varphi) \ \psi$
by *auto*

lemma *elim-imp-explicit*: *elim-imp* $\varphi \ \psi \Longrightarrow \forall A. A \models \varphi \longleftrightarrow A \models \psi$
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-consistant*:
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*:
 $\text{wf-conn } c \ l \Longrightarrow \text{no-imp-symb } (\text{conn } c \ l) \longleftrightarrow c \neq \text{CImp}$
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*]:
 $\neg \text{no-imp } (\text{FImp } \varphi \ \psi)$
 $\text{no-imp } \text{FT}$
 $\text{no-imp } \text{FF}$
unfolding *no-imp-def* **by** *auto*

lemma *all-subformula-st-decomp-explicit-imp*[*simp*]:
fixes $\varphi \ \psi :: 'v \text{ propo}$
shows

$\text{no-imp } (\text{FNot } \varphi) \longleftrightarrow \text{no-imp } \varphi$
 $\text{no-imp } (\text{FAnd } \varphi \ \psi) \longleftrightarrow (\text{no-imp } \varphi \wedge \text{no-imp } \psi)$
 $\text{no-imp } (\text{FOr } \varphi \ \psi) \longleftrightarrow (\text{no-imp } \varphi \wedge \text{no-imp } \psi)$
by *auto*

Invariant of the *elim-imp* transformation

lemma *elim-imp-no-equiv*:
 $\text{elim-imp } \varphi \ \psi \Longrightarrow \text{no-equiv } \varphi \Longrightarrow \text{no-equiv } \psi$
by (*induct* $\varphi \ \psi$ *rule*: *elim-imp.induct*, *auto*)

lemma *elim-imp-inv*:
fixes $\varphi \ \psi :: 'v \text{ propo}$

```

assumes full (propo-rew-step elim-imp)  $\varphi \psi$ 
and no-equiv  $\varphi$ 
shows no-equiv  $\psi$ 
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  $\varphi :: 'v \text{ propo}$ 
  assumes no-equiv:  $\neg \text{no-imp } \varphi$ 
  shows  $\exists \psi \psi'. \psi \preceq \varphi \wedge \text{elim-imp } \psi \psi'$ 
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  $c :: 'v \text{ connective}$  and  $l :: 'v \text{ propo list}$  and  $\psi :: 'v \text{ propo}$ 
    have  $H: \text{elim-imp } (\text{conn } c \ l) \ \psi \implies \neg \text{no-imp-symb } (\text{conn } c \ l)$ 
      by (auto elim: elim-imp.cases)
  }
  moreover
    have  $H': \forall \psi. \neg \text{elim-imp } FT \ \psi \ \forall \psi. \neg \text{elim-imp } FF \ \psi \ \forall \psi \ x. \neg \text{elim-imp } (FVar \ x) \ \psi$ 
      by (auto elim: elim-imp.cases)+
    moreover have  $\bigwedge \varphi. \neg \text{no-imp-symb } \varphi \implies \exists \psi. \text{elim-imp } \varphi \ \psi$ 
      apply (case-tac  $\varphi$ ) using elim-imp.simps by force+
    hence  $(\bigwedge \varphi'. \varphi' \preceq \varphi \implies \neg \text{no-imp-symb } \varphi' \implies \exists \psi. \text{elim-imp } \varphi' \ \psi)$  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)  $\varphi \psi \implies \text{no-imp } \psi$ 
  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  $\varphi$  FT)  $\varphi$  |
ElimTB1': elimTB (FAnd FT  $\varphi$ )  $\varphi$  |

```

```

ElimTB2: elimTB (FAnd  $\varphi$  FF) FF |
ElimTB2': elimTB (FAnd FF  $\varphi$ ) FF |

```

```

ElimTB3: elimTB (FOr  $\varphi$  FT) FT |
ElimTB3': elimTB (FOr FT  $\varphi$ ) FT |

```

```

ElimTB4: elimTB (FOr  $\varphi$  FF)  $\varphi$  |
ElimTB4': elimTB (FOr FF  $\varphi$ )  $\varphi$  |

```

```

ElimTB5: elimTB (FNot FT) FF |
ElimTB6: elimTB (FNot FF) FT

```

lemma elimTB-consistent: preserves-un-sat elimTB

proof –

```

{
  fix  $\varphi \psi :: 'b \text{ propo}$ 
  have  $\text{elimTB } \varphi \psi \implies \forall A. A \models \varphi \longleftrightarrow A \models \psi$  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:  $c \neq CF \implies c \neq CT \implies \text{wf-conn } c \ l \implies (\forall \varphi \in \text{set } l. \varphi \neq FT \wedge \varphi \neq FF)$ 
 $\implies \text{no-T-F-symb } (\text{conn } c \ l)$ 

```

```

lemma wf-conn-no-T-F-symb-iff[simp]:
  wf-conn c  $\psi$ s  $\implies \text{no-T-F-symb } (\text{conn } c \ \psi$ 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
     $\neg \text{no-T-F-symb } (FT :: 'v \text{ propo})$ 
     $\neg \text{no-T-F-symb } (FF :: 'v \text{ propo})$ 
  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:
   $\neg \text{no-T-F-symb } (FNot \ \varphi) \implies \varphi = FT \vee \varphi = FF$ 
proof (rule ccontr)
  assume n:  $\neg \text{no-T-F-symb } (FNot \ \varphi)$ 

```



```

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  $(metis \text{ conn.simps}(4) \text{ connective.distinct}(5,17))$ 
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  $(metis \text{ conn-inj-not}(2) \text{ list.set-intros}(1))$ 

```

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  $\varphi \implies \text{no-T-F-symb-except-toplevel } \varphi$ 

```

```

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:
   $\varphi \neq FT \implies \varphi \neq FF \implies \text{no-T-F-symb-except-toplevel } (FNot \varphi)$ 
  by simp

```

```

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

```

```

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

```

```

lemma no-T-F-symb-except-top-level-false-example $[simp]$ :
  fixes  $\varphi \psi :: 'v \text{ propo}$ 
  assumes  $\varphi = FT \vee \psi = FT \vee \varphi = FF \vee \psi = FF$ 
  shows
     $\neg \text{no-T-F-symb-except-toplevel } (FAnd \ \varphi \ \psi)$ 
     $\neg \text{no-T-F-symb-except-toplevel } (FOr \ \varphi \ \psi)$ 

```

\neg *no-T-F-symb-except-toplevel* (*FImp* φ ψ)
 \neg *no-T-F-symb-except-toplevel* (*FEq* φ ψ)
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 φ $\psi :: 'v$ *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 $FT \in \text{set } l \vee FF \in \text{set } l$
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 φ $\psi :: 'v$ *propo*
assumes $\varphi = FT \vee \psi = FT \vee \varphi = FF \vee \psi = FF$
shows
 \neg *no-T-F-except-top-level* (*FAnd* φ ψ)
 \neg *no-T-F-except-top-level* (*FOr* φ ψ)
 \neg *no-T-F-except-top-level* (*FEq* φ ψ)
 \neg *no-T-F-except-top-level* (*FImp* φ ψ)
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 $\varphi \longleftrightarrow (\varphi = FF \vee \varphi = FT \vee \text{no-T-F } \varphi)$
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 *no-T-F (conn c [φ , ψ]) \longleftrightarrow (no-T-F $\varphi \wedge$ no-T-F ψ)*
proof –
have *wf: wf-conn c [φ , ψ] using c by auto*
hence *no-T-F (conn c [φ , ψ]) \longleftrightarrow (no-T-F-symb (conn c [φ , ψ]) \wedge no-T-F $\varphi \wedge$ no-T-F ψ)*
by (*simp add: all-subformula-st-decomp no-T-F-def*)
thus *no-T-F (conn c [φ , ψ]) \longleftrightarrow (no-T-F $\varphi \wedge$ no-T-F ψ)*
using *c wf all-subformula-st-decomp list.discI no-T-F-def 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) 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 *no-T-F (conn c [φ , ψ]) \longleftrightarrow (no-T-F $\varphi \wedge$ no-T-F ψ)*
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
no-T-F (FAnd $\varphi \psi$) \longleftrightarrow (no-T-F $\varphi \wedge$ no-T-F ψ)
no-T-F (FOr $\varphi \psi$) \longleftrightarrow (no-T-F $\varphi \wedge$ no-T-F ψ)
no-T-F (FEq $\varphi \psi$) \longleftrightarrow (no-T-F $\varphi \wedge$ no-T-F ψ)
no-T-F (FImp $\varphi \psi$) \longleftrightarrow (no-T-F $\varphi \wedge$ no-T-F ψ)
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 *no-T-F (FNot φ) \longleftrightarrow no-T-F φ*
by (*metis all-subformula-st-decomp-explicit(3) all-subformula-st-test-symb-true-phi no-T-F-def*
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 *φ : no-T-F (FAnd $\varphi \psi$) \vee no-T-F (FOr $\varphi \psi$) \vee no-T-F (FEq $\varphi \psi$) \vee no-T-F (FImp $\varphi \psi$)*
shows *no-T-F ψ and no-T-F φ*
using *assms by auto*

lemma *no-T-F-decomp-not*:
fixes *$\varphi :: 'v \text{ propo}$*
assumes *φ : no-T-F (FNot φ)*

```

shows no-T-F  $\varphi$ 
using assms by auto

lemma no-T-F-symb-except-toplevel-step-exists:
  fixes  $\varphi \ \psi :: 'v \text{ propo}$ 
  assumes no-equiv  $\varphi$  and 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  $\psi$  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  $\psi$ )
  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  $\varphi' \ \psi1 \ \psi2$ )
  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  $\varphi' = FImp \ \psi1 \ \psi2 \vee \varphi' = FEq \ \psi1 \ \psi2$ 
    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  $\varphi': \varphi' = FAnd \ \psi1 \ \psi2 \vee \varphi' = FOr \ \psi1 \ \psi2$ 
    hence  $\psi1 = FT \vee \psi2 = FT \vee \psi1 = FF \vee \psi2 = FF$ 
    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  $\varphi :: 'v \text{ propo}$ 
  assumes noTB:  $\neg \text{no-T-F-except-top-level } \varphi$  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  $c:: 'v \text{ connective}$  and  $l:: 'v \text{ propo list}$  and  $\psi:: 'v \text{ propo}$ 
    have  $H: \text{elimTB } (\text{conn } c \ l) \ \psi \implies \neg \text{no-T-F-symb-except-toplevel } (\text{conn } c \ l)$ 
      by (cases (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  $\psi \preceq \varphi \implies \neg \text{no-}T\text{-}F\text{-symb-except-toplevel } \psi \implies \exists \psi'. \text{elimTB } \psi \psi'$ 
    using  $\text{no-}T\text{-}F\text{-symb-except-toplevel-step-exists no-equiv no-imp}$  by auto
}
ultimately show ?thesis
  using  $\text{no-test-symb-step-exists noTB unfolding no-}T\text{-}F\text{-except-top-level-def}$  by blast
qed

```

```

lemma elimTB-inv:
  fixes  $\varphi \psi :: 'v \text{ propo}$ 
  assumes  $\text{full (propo-rew-step elimTB) } \varphi \psi$ 
  and  $\text{no-equiv } \varphi$  and  $\text{no-imp } \varphi$ 
  shows  $\text{no-equiv } \psi$  and  $\text{no-imp } \psi$ 
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 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  $\text{no-}T\text{-}F\text{-except-top-level } \psi$ 
  using  $\text{full-propo-rew-step-subformula no-}T\text{-}F\text{-except-top-level-rew assms elimTB-inv}$  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 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 pushNeg-consistent: preserves-un-sat pushNeg
  unfolding preserves-un-sat-def by (simp add: pushNeg-explicit)

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

fun simple where
  simple FT = True |
  simple FF = True |
  simple (FVar _) = True |
  simple - = False

lemma simple-decomp:
  simple  $\varphi \longleftrightarrow (\varphi = FT \vee \varphi = FF \vee (\exists x. \varphi = FVar\ x))$ 
  by (cases  $\varphi$ ) auto

lemma subformula-conn-decomp-simple:
  fixes  $\varphi \psi :: 'v$  propo
  assumes s: simple  $\psi$ 
  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  $\varphi$ ) = (simple  $\varphi$ ) |
  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  $\varphi$  and no-imp  $\varphi$ 

```

```

shows  $\psi \preceq \varphi \implies \neg \text{simple-not-symb } \psi \implies \exists \psi'. \text{pushNeg } \psi \psi'$ 
apply (induct  $\psi$ , auto)
apply (rename-tac  $\psi$ , case-tac  $\psi$ , auto intro: pushNeg.intros)
by (metis assms(1,2) no-imp-Impl(1) no-equiv-eq(1) no-imp-def no-equiv-def
    subformula-in-subformula-not subformula-all-subformula-st)+

lemma simple-not-rew:
  fixes  $\varphi :: 'v \text{ propo}$ 
  assumes noTB:  $\neg \text{simple-not } \varphi$  and no-equiv: no-equiv  $\varphi$  and no-imp: no-imp  $\varphi$ 
  shows  $\exists \psi \psi'. \psi \preceq \varphi \wedge \text{pushNeg } \psi \psi'$ 
proof -
  have  $\forall x. \text{simple-not-symb } (FF :: 'v \text{ propo}) \wedge \text{simple-not-symb } FT \wedge \text{simple-not-symb } (FVar (x :: 'v))$ 
    by auto
  moreover {
    fix  $c :: 'v \text{ connective}$  and  $l :: 'v \text{ propo list}$  and  $\psi :: 'v \text{ propo}$ 
    have  $H: \text{pushNeg } (\text{conn } c \ l) \ \psi \implies \neg \text{simple-not-symb } (\text{conn } c \ l)$ 
      by (cases (conn c l) rule: pushNeg.cases) auto
  }
  moreover {
    fix  $x :: 'v$ 
    have  $H': \text{simple-not } FT \text{ simple-not } FF \text{ simple-not } (FVar \ x)$ 
      by simp-all
  }
  moreover {
    fix  $\psi :: 'v \text{ propo}$ 
    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  $c \neq CF \wedge c \neq CT \wedge$  wf-conn  $c (\xi @ \varphi' \# \xi')$ 
  using wf-conn-no-arity-change-helper wf-conn-no-arity-change by metis
moreover have  $n'$ : 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 ψ

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 propo

assumes full (propo-rew-step pushNeg) $\varphi \psi$

and no-equiv φ and no-imp φ and no-T-F-except-top-level φ

shows no-equiv ψ and no-imp ψ and no-T-F-except-top-level ψ

proof –

```

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

```

8.5 Push inside

```

inductive 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
  push-conn-inside-l[simp]:  $c = CAnd \vee c = COr \implies c' = CAnd \vee c' = COr$ 
     $\implies \text{push-conn-inside } c \ c' (\text{conn } c [\text{conn } c' [\varphi 1, \varphi 2], \psi])$ 
     $(\text{conn } c' [\text{conn } c [\varphi 1, \psi], \text{conn } c [\varphi 2, \psi]]) \mid$ 
  push-conn-inside-r[simp]:  $c = CAnd \vee c = COr \implies c' = CAnd \vee c' = COr$ 
     $\implies \text{push-conn-inside } c \ c' (\text{conn } c [\psi, \text{conn } c' [\varphi 1, \varphi 2]])$ 
     $(\text{conn } c' [\text{conn } c [\psi, \varphi 1], \text{conn } c [\psi, \varphi 2]])$ 

```

```

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

```

```

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

```

```

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

```

\neg propo-rew-step (push-conn-inside c c') FT ψ
 \neg propo-rew-step (push-conn-inside c c') FF ψ **by** blast+
qed

inductive not-c-in-c'-symb:: ' v connective \Rightarrow ' v connective \Rightarrow ' v propo \Rightarrow bool **for** c c' **where**
 not-c-in-c'-symb-l[simp]: wf-conn c [conn c' [φ , φ'], ψ] \Longrightarrow wf-conn c' [φ , φ']
 \Longrightarrow not-c-in-c'-symb c c' (conn c [conn c' [φ , φ'], ψ)] |
 not-c-in-c'-symb-r[simp]: wf-conn c [ψ , conn c' [φ , φ']] \Longrightarrow wf-conn c' [φ , φ']
 \Longrightarrow not-c-in-c'-symb c c' (conn c [ψ , conn c' [φ , φ']])

abbreviation c-in-c'-symb c c' $\varphi \equiv \neg$ not-c-in-c'-symb c c' φ

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

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

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' $\xi \Longrightarrow$ wf-conn c [φ , ψ] $\Longrightarrow \xi =$ conn c [φ , ψ]
 \Longrightarrow not-c-in-c'-symb c c' (conn c [ψ , φ])

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

case (not-c-in-c'-symb-r φ' φ'' ψ') **note** $H =$ this

hence ψ : $\psi =$ conn c' [φ'' , ψ'] **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 φ' φ'' ψ') **note** $H =$ this

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

moreover have $wf\text{-}conn\ c\ [\psi',\ conn\ c'\ [\varphi',\ \varphi']]$
using $H(1)\ wf\text{-}conn\text{-}no\text{-}arity\text{-}change\ length\text{-}Cons$ **by** $metis$
ultimately show $not\text{-}c\text{-}in\text{-}c'\text{-}symb\ c\ c'\ (conn\ c\ [\psi,\ \varphi])$
using $not\text{-}c\text{-}in\text{-}c'\text{-}symb.intros(2)\ conn\text{-}inj\ not\text{-}c\text{-}in\text{-}c'\text{-}symb\text{-}l.hyps$
 $not\text{-}c\text{-}in\text{-}c'\text{-}symb\text{-}l.prem(1,2)$ **by** $blast$
qed

lemma $not\text{-}c\text{-}in\text{-}c'\text{-}symb\text{-}commute'$:
 $wf\text{-}conn\ c\ [\varphi,\ \psi] \implies c\text{-}in\text{-}c'\text{-}symb\ c\ c'\ (conn\ c\ [\varphi,\ \psi]) \longleftrightarrow c\text{-}in\text{-}c'\text{-}symb\ c\ c'\ (conn\ c\ [\psi,\ \varphi])$
using $not\text{-}c\text{-}in\text{-}c'\text{-}symb\text{-}commute\ wf\text{-}conn\text{-}no\text{-}arity\text{-}change$ **by** $(metis\ length\text{-}Cons)$

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

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

lemma $c\text{-}in\text{-}c'\text{-}symb\text{-}not[simp]$:
fixes $c\ c' :: 'v\ connective$ **and** $\psi :: 'v\ propo$
shows $c\text{-}in\text{-}c'\text{-}symb\ c\ c'\ (FNot\ \psi)$
proof –
{
fix $\xi :: 'v\ propo$
have $not\text{-}c\text{-}in\text{-}c'\text{-}symb\ c\ c'\ (FNot\ \psi) \implies False$
apply $(induct\ FNot\ \psi\ rule:\ not\text{-}c\text{-}in\text{-}c'\text{-}symb.induct)$
using $conn\text{-}inj\text{-}not(2)$ **by** $blast+$
}
thus $?thesis$ **by** $auto$
qed

lemma $c\text{-}in\text{-}c'\text{-}symb\text{-}step\text{-}exists$:

```

fixes  $\varphi :: 'v \text{ propo}$ 
assumes  $c: c = CAnd \vee c = COr$  and  $c': c' = CAnd \vee c' = COr$ 
shows  $\psi \preceq \varphi \implies \neg c\text{-in-}c'\text{-symb } c \ c' \ \psi \implies \exists \psi'. \text{push-conn-inside } c \ c' \ \psi \ \psi'$ 
apply (induct  $\psi$  rule: propo-induct-arity)
apply auto[2]
proof –
  fix  $\psi1 \ \psi2 \ \varphi' :: 'v \text{ propo}$ 
  assume  $IH\psi1: \psi1 \preceq \varphi \implies \neg c\text{-in-}c'\text{-symb } c \ c' \ \psi1 \implies Ex (\text{push-conn-inside } c \ c' \ \psi1)$ 
  and  $IH\psi2: \psi2 \preceq \varphi \implies \neg c\text{-in-}c'\text{-symb } c \ c' \ \psi2 \implies Ex (\text{push-conn-inside } c \ c' \ \psi2)$ 
  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  $n: \text{not-}c\text{-in-}c'\text{-symb } c \ c' \ \varphi'$  by auto
  {
    assume  $\varphi': \varphi' = \text{conn } c \ [\psi1, \psi2]$ 
    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)  $c \ c' \ n \ \text{push-conn-inside-l} \ \text{push-conn-inside-r}$ )
  }
  ultimately show  $Ex (\text{push-conn-inside } c \ c' \ \varphi')$  by blast
qed

```

lemma $c\text{-in-}c'\text{-symb-rew}$:

```

fixes  $\varphi :: 'v \text{ propo}$ 
assumes  $noTB: \neg c\text{-in-}c'\text{-only } c \ c' \ \varphi$ 
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  $\text{test-symb-false-nullary}$ :
     $\forall x. c\text{-in-}c'\text{-symb } c \ c' \ (FF::'v \text{ propo}) \wedge c\text{-in-}c'\text{-symb } c \ c' \ FT$ 
     $\wedge c\text{-in-}c'\text{-symb } c \ c' \ (FVar \ (x::'v))$ 
  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)  $c' \ c\text{-in-}c'\text{-symb-step-exists}$ )
  }
  ultimately show  $?thesis$  using  $noTB \ \text{no-test-symb-step-exists}[of \ c\text{-in-}c'\text{-symb } c \ c']$ 

```

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 *propo-rew-step* (*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 *no-T-F* ψ

by (*cases rule: push-conn-inside.cases, auto*)

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)

have *no-T-F* φ

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 φ' : *no-T-F* φ' **using** *IH* **by** *blast*

have $\forall \zeta \in \text{set } (\xi @ \varphi \# \xi'). \text{no-T-F } \zeta$ **by** (*metis wf no-T-F no-T-F-def all-subformula-st-decomp*)

hence *n*: $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi'). \text{no-T-F } \zeta$ **using** φ' **by** *auto*

hence *n'*: $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi'). \zeta \neq FF \wedge \zeta \neq FT$

using φ' **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* φ' *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'*) $\varphi \psi \implies \text{simple } \varphi \implies \text{simple } \psi$

apply (*induct rule: propo-rew-step.induct*)

apply (*rename-tac* φ , *case-tac* φ , *auto simp add: push-conn-inside.simps*)[]

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 $c\ c' :: 'v\ \text{connective}$ **and** $\varphi\ \psi :: 'v\ \text{propo}$
shows *propo-rew-step (push-conn-inside c c') $\varphi\ \psi \implies \text{simple-not } \varphi \implies \text{simple-not } \psi$*
proof (*induct rule: propo-rew-step.induct*)
case (*global-rel $\varphi\ \psi$*)
thus ?case **by** (*cases φ , auto simp add: push-conn-inside.simps*)
next
case (*propo-rew-one-step-lift $\varphi\ \varphi'\ ca\ \xi\ \xi'$*) **note** *rew = this(1)* **and** *IH = this(2)* **and** *wf = this(3)*
and *simple = this(4)*
show ?case
proof (*cases ca rule: connective-cases-arity*)
case *nullary*
then show ?thesis **using** *propo-rew-one-step-lift* **by** *auto*
next
case *binary* **note** *ca = this*
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 $\forall \zeta \in \text{set } (\xi\ @\ \varphi \# \xi').\ \text{simple-not } \zeta$
by (*metis wf all-subformula-st-decomp simple simple-not-def*)
hence $\forall \zeta \in \text{set } (\xi\ @\ \varphi' \# \xi').\ \text{simple-not } \zeta$ **using** *IH* **by** *simp*
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 ?thesis
by (*simp add: ab all-subformula-st-decomp ca*)
next
case *unary*
then show ?thesis
using *rew simple-propo-rew-step-push-conn-inside-inv[OF rew] IH local.wf simple* **by** *auto*
qed
qed

lemma *propo-rew-step-push-conn-inside-simple-not*:
fixes $\varphi\ \varphi' :: 'v\ \text{propo}$ **and** $\xi\ \xi' :: 'v\ \text{propo list}$ **and** $c :: 'v\ \text{connective}$
assumes
propo-rew-step (push-conn-inside c c') $\varphi\ \varphi'$ and
wf-conn c ($\xi\ @\ \varphi \# \xi'$) and
simple-not-symb (conn c ($\xi\ @\ \varphi \# \xi'$)) and
simple-not-symb φ'
shows *simple-not-symb (conn c ($\xi\ @\ \varphi' \# \xi'$))*
using *assms*
proof (*induction rule: propo-rew-step.induct*)
print-cases
case (*global-rel*)
then show ?case
by (*metis conn.simps(12,17) list.discI push-conn-inside.cases simple-not-symb.elims(3)*
wf-conn-helper-facts(5) wf-conn-list(2) wf-conn-list(8) wf-conn-no-arity-change
wf-conn-no-arity-change-helper)
next
case (*propo-rew-one-step-lift $\varphi\ \varphi'\ c'\ \chi s\ \chi s'$*) **note** *tel = this(1)* **and** *wf = this(2)* **and** *IH = this(3)*
and *wf' = this(4)* **and** *simple' = this(5)* **and** *simple = this(6)*
then show ?case
proof (*cases c' rule: connective-cases-arity*)
case *nullary*

```

    then show ?thesis using wf simple simple' by auto
next
case binary note c = this(1)
have corr': wf-conn c (ξ @ conn c' (χs @ φ' # χs') # ξ')
  using wf wf-conn-no-arity-change
  by (metis wf' wf-conn-no-arity-change-helper)
then show ?thesis
  using c propo-rew-one-step-lift wf
  by (metis conn.simps(17) connective.distinct(37) propo-rew-step-subformula-imp
      push-conn-inside.cases simple-not-symb.elims(3) wf-conn.simps wf-conn-list(2,8))
next
case unary
then have empty: χs = [] χs' = [] using wf by auto
then show ?thesis using simple unary simple' wf wf'
  by (metis connective.distinct(37) connective.distinct(39) propo-rew-step-subformula-imp
      push-conn-inside.cases simple-not-symb.elims(3) tel wf-conn-list(8)
      wf-conn-no-arity-change wf-conn-no-arity-change-helper)
qed
qed

```

lemma *push-conn-inside-not-true-false:*
push-conn-inside c c' φ ψ ⇒ ψ ≠ FT ∧ ψ ≠ FF
by (induct rule: *push-conn-inside.induct*, auto)

lemma *push-conn-inside-inv:*
fixes φ ψ :: 'v propo
assumes full (propo-rew-step (push-conn-inside c c') φ ψ
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 φ ψ :: 'v propo
have H: *push-conn-inside c c' φ ψ ⇒ all-subformula-st simple-not-symb φ*
⇒ all-subformula-st simple-not-symb ψ
by (induct φ ψ rule: *push-conn-inside.induct*, auto)
} note H = this
}

fix φ ψ :: 'v propo
have H: *propo-rew-step (push-conn-inside c c') φ ψ ⇒ all-subformula-st simple-not-symb φ*
⇒ all-subformula-st simple-not-symb ψ
apply (induct φ ψ rule: *propo-rew-step.induct*)
using H **apply** *simp*
proof (rename-tac φ φ' ca ψs ψs', case-tac ca rule: *connective-cases-arity*)
fix φ φ' :: 'v propo **and** c:: 'v connective **and** ξ ξ':: 'v propo list
and x:: 'v
assume wf-conn c (ξ @ φ # ξ')
and c = CT ∨ c = CF ∨ c = CVar x
hence ξ @ φ # ξ' = [] **by** auto
hence False **by** auto
thus *all-subformula-st simple-not-symb (conn c (ξ @ φ' # ξ'))* **by** blast
next
fix φ φ' :: 'v propo **and** ca:: 'v connective **and** ξ ξ':: 'v propo list
and x :: 'v
assume rel: *propo-rew-step (push-conn-inside c c') φ φ'*


```

and  $\varphi\text{-}\varphi'$ : 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  $c$ :  $ca = CNot$ 

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  $\varphi\text{-}\varphi'$  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  $c$ :  $ca \in \text{binary-connectives}$ 

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  $\chi \vee \chi \notin \text{set } (\xi @ \varphi' \# \xi')$ 
    using  $wf'$  by (metis (no-types)  $\varphi'$  all-subformula-st-decomp calculation insert-iff
      list.set(2))
}
hence  $\forall \varphi. \varphi \in \text{set } (\xi @ \varphi' \# \xi') \longrightarrow$  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  $\xi \xi' :: 'v \text{propo list and } \varphi \varphi' :: 'v \text{propo}$ 
have propo-rew-step (push-conn-inside c c')  $\varphi \varphi' \implies \text{wf-conn ca } (\xi @ \varphi \# \xi')$ 
 $\implies \text{simple-not-symb (conn ca } (\xi @ \varphi \# \xi')) \implies \text{simple-not-symb } \varphi'$ 
 $\implies \text{simple-not-symb (conn ca } (\xi @ \varphi' \# \xi'))$ 
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  $\varphi \psi :: 'v \text{propo}$ 
have H: propo-rew-step (push-conn-inside c c')  $\varphi \psi \implies \text{no-T-F-except-top-level } \varphi$ 
 $\implies \text{no-T-F-except-top-level } \psi$ 
proof -
assume rel: propo-rew-step (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  $\xi \xi' :: 'v \text{propo list and } \varphi \varphi' :: 'v \text{propo}$ 
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  $\varphi \psi :: 'v$  propo
  have  $H$ : push-conn-inside  $c$   $c'$   $\varphi \psi \implies$  no-equiv  $\varphi \implies$  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  $\varphi \psi :: 'v$  propo
  have  $H$ : push-conn-inside  $c$   $c'$   $\varphi \psi \implies$  no-imp  $\varphi \implies$  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 $\varphi \psi :: 'v$ propo

assumes

- no-equiv φ and*
- no-imp φ and*
- full (propo-rew-step (push-conn-inside c c')) $\varphi \psi$ and*
- no-T-F-except-top-level φ and*
- simple-not φ and*
- $c = CAnd \vee c = COr$ and*
- $c' = CAnd \vee c' = COr$*

shows *c -in- c' -only c c' ψ*

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* $:: 'v$ connective $\Rightarrow 'v$ propo \Rightarrow bool **for** $c :: 'v$ connective **where**

- simple-only-c-inside[simp]: simple $\varphi \implies$ only-c-inside-symb c φ |*
- simple-cnot-only-c-inside[simp]: simple $\varphi \implies$ only-c-inside-symb c (FNot φ) |*
- only-c-inside-into-only-c-inside: wf-conn c $l \implies$ only-c-inside-symb c (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 $c =$ all-subformula-st (only-c-inside-symb c)*

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

$only-c-inside-symb\ c\ \psi \longleftrightarrow (simple\ \psi \vee (\exists\ \varphi'.\ \psi = FNot\ \varphi' \wedge simple\ \varphi') \vee (\exists\ l.\ \psi = conn\ c\ l \wedge wf-conn\ c\ l))$
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 ψ 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 φ'
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 $l :: 'v \text{ propo list}$ **and** $c \ c' \ ca :: 'v \text{ connective}$

shows $\text{wf-conn } ca \ l \implies ca \neq c \implies c\text{-in-}c'\text{-symb } c \ c' \ (\text{conn } ca \ l)$

proof –

have $\text{not-}c\text{-in-}c'\text{-symb } c \ c' \ (\text{conn } ca \ l) \implies \text{wf-conn } ca \ l \implies ca = c$

by (*induct conn ca l rule: not-c-in-c'-symb.induct, auto simp add: conn-inj*)

thus $\text{wf-conn } ca \ l \implies ca \neq c \implies c\text{-in-}c'\text{-symb } c \ c' \ (\text{conn } ca \ l)$ **by** *blast*

qed

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

assumes $\delta: c \neq c' \text{ and } c: c = CAnd \vee c = COr \text{ and } c': c' = CAnd \vee c' = COr$

shows $\text{only-c-inside } c \ \varphi \implies c\text{-in-}c'\text{-only } c \ c' \ \varphi$

unfolding *c-in-c'-only-def all-subformula-st-def*

using *only-c-inside-implies-c-in-c'-symb*

by (*metis all-subformula-st-def assms(1) c c' only-c-inside-def subformula-trans*)

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

assumes $\delta: c = CAnd \vee c = COr \ c' = CAnd \vee c' = COr \ c \neq c' \text{ and } \text{wf}: \text{wf-conn } c \ [\varphi, \psi]$

and *inv: no-equiv (conn c l) no-imp (conn c l) simple-not (conn c l)*

shows $\text{wf-conn } c \ l \implies c\text{-in-}c'\text{-only } c \ c' \ (\text{conn } c \ l) \implies (\forall \psi \in \text{set } l. \text{only-c-inside } c \ \psi)$

using *inv*

proof (*induct conn c l arbitrary: l rule: propo-induct-arity*)

case (*nullary x*)

thus *?case* **by** (*auto simp add: wf-conn-list assms*)

next

case (*unary $\varphi \ la$*)

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

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

next

case (*binary $\varphi_1 \ \varphi_2$*)

note $IH\varphi_1 = \text{this}(1)$ **and** $IH\varphi_2 = \text{this}(2)$ **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 $l: l = [\varphi_1, \varphi_2]$ **by** (*meson wf-conn-list(4-7)*)

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

obtain $c1 \ l1 \ c2 \ l2$ **where** $\varphi_1: \varphi_1 = \text{conn } c1 \ l1$ **and** $\text{wf}\varphi_1: \text{wf-conn } c1 \ l1$

and $\varphi_2: \varphi_2 = \text{conn } c2 \ l2$ **and** $\text{wf}\varphi_2: \text{wf-conn } c2 \ l2$ **using** *exists-c-conn* **by** *metis*

hence $c\text{-in-}c'\text{-only}\varphi_1: c\text{-in-}c'\text{-only } c \ c' \ (\text{conn } c1 \ l1)$ **and** $c\text{-in-}c'\text{-only } c \ c' \ (\text{conn } c2 \ l2)$

using *only l* **unfolding** *c-in-c'-only-def* **using** *assms(1)* **by** *auto*

have $\text{inc}\varphi_1: \varphi_1 \preceq ? \varphi$ **and** $\text{inc}\varphi_2: \varphi_2 \preceq ? \varphi$

using $\varphi_1 \ \varphi_2 \ \varphi \text{ local.wf}$ **by** (*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** $\text{inc}\varphi_1 \ \text{inc}\varphi_2$ **by** (*metis $\varphi_1 \ \varphi_2 \ \text{wf}\varphi_1 \ \text{wf}\varphi_2 \ \text{assms}(1) \ \text{no-equiv} \ \text{no-equiv-eq}(1) \ \text{no-equiv-symb.elims}(3) \ \text{no-equiv-symb-conn-characterization} \ \text{wf-conn-list}(4,5) \ \text{no-equiv-def} \ \text{subformula-all-subformula-st}$*)+

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

using *no-imp* **by** (*metis $\varphi_1 \ \varphi_2 \ \text{all-subformula-st-decomp-explicit-imp}(2,3) \ \text{assms}(1) \ \text{conn.simps}(5,6) \ l \ \text{no-imp-imp}(1) \ \text{no-imp-symb.elims}(3) \ \text{no-imp-symb-conn-characterization} \ \text{wf}\varphi_1 \ \text{wf}\varphi_2 \ \text{all-subformula-st-decomp} \ \text{no-imp-symb-conn-characterization}$*)+

have $c1c: c1 \neq c'$

proof

```

assume  $c1c: c1 = c'$ 
then obtain  $\xi1 \ \xi2$  where  $l1: l1 = [\xi1, \xi2]$ 
  by (metis assms(2) connective.distinct(37,39) helper-fact wf $\varphi1$  wf-conn.simps
    wf-conn-list-decomp(1-3))
  have c-in-c'-only  $c \ c'$  (conn  $c$  [conn  $c'$   $l1$ ,  $\varphi2$ ]) using  $c1c \ l$  only  $\varphi1$  by auto
  moreover have not-c-in-c'-symb  $c \ c'$  (conn  $c$  [conn  $c'$   $l1$ ,  $\varphi2$ ])
    using  $l1 \ \varphi1 \ c1c \ l$  local.wf not-c-in-c'-symb-l wf $\varphi1$  by blast
  ultimately show False using  $\varphi1 \ c1c \ l \ l1$  local.wf not-c-in-c'-simp(4) wf $\varphi1$  by blast
qed
hence ( $\varphi1 = \text{conn } c \ l1 \wedge \text{wf-conn } c \ l1$ )  $\vee$  ( $\exists \psi1. \varphi1 = \text{FNot } \psi1$ )  $\vee$  simple  $\varphi1$ 
  by (metis  $\varphi1$  assms(1-3) c1-eq c1-imp simple.elims(3) wf $\varphi1$  wf-conn-list(4) wf-conn-list(5-7))
moreover {
  assume  $\varphi1 = \text{conn } c \ l1 \wedge \text{wf-conn } c \ l1$ 
  hence only-c-inside  $c \ \varphi1$ 
  by (metis IH $\varphi1 \ \varphi1$  all-subformula-st-decomp-imp inc $\varphi1$  no-equiv no-equiv-def no-imp no-imp-def
    c-in-only $\varphi1$  only-c-inside-def only-c-inside-into-only-c-inside simple-not simple-not-def
    subformula-all-subformula-st)
}
moreover {
  assume  $\exists \psi1. \varphi1 = \text{FNot } \psi1$ 
  then obtain  $\psi1$  where  $\varphi1 = \text{FNot } \psi1$  by metis
  hence only-c-inside  $c \ \varphi1$ 
  by (metis all-subformula-st-def assms(1) connective.distinct(37,39) inc $\varphi1$ 
    only-c-inside-decomp-not simple-not simple-not-def simple-not-symb.simps(1))
}
moreover {
  assume simple  $\varphi1$ 
  hence only-c-inside  $c \ \varphi1$ 
  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 $\varphi1: \text{only-c-inside } c \ \varphi1$  by metis

have c-in-only $\varphi2: \text{c-in-c'-only } c \ c'$  (conn  $c2 \ l2$ )
  using only  $l \ \varphi2 \ \text{wf}\varphi2$  assms unfolding c-in-c'-only-def by auto
have  $c2c: c2 \neq c'$ 
proof
  assume  $c2c: c2 = c'$ 
  then obtain  $\xi1 \ \xi2$  where  $l2: l2 = [\xi1, \xi2]$ 
  by (metis assms(2) wf $\varphi2$  wf-conn.simps connective.distinct(7,9,19,21,29,31,37,39))
  hence c-in-c'-symb  $c \ c'$  (conn  $c$  [ $\varphi1$ , conn  $c'$   $l2$ ])
    using  $c2c \ l$  only  $\varphi2$  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  $c$  [ $\varphi1$ , conn  $c'$   $l2$ ])
    using assms(1)  $c2c \ l2$  not-c-in-c'-symb-r wf $\varphi2$  wf-conn-helper-facts(5,6) by metis
  ultimately show False by auto
qed
hence ( $\varphi2 = \text{conn } c \ l2 \wedge \text{wf-conn } c \ l2$ )  $\vee$  ( $\exists \psi2. \varphi2 = \text{FNot } \psi2$ )  $\vee$  simple  $\varphi2$ 
  using c2-eq by (metis  $\varphi2$  assms(1-3) c2-eq c2-imp simple.elims(3) wf $\varphi2$  wf-conn-list(4-7))
moreover {
  assume  $\varphi2 = \text{conn } c \ l2 \wedge \text{wf-conn } c \ l2$ 
  hence only-c-inside  $c \ \varphi2$ 
  by (metis IH $\varphi2 \ \varphi2$  all-subformula-st-decomp inc $\varphi2$  no-equiv no-equiv-def no-imp no-imp-def
    c-in-only $\varphi2$  only-c-inside-def only-c-inside-into-only-c-inside simple-not simple-not-def
    subformula-all-subformula-st)
}

```

```

moreover {
  assume  $\exists \psi 2. \varphi 2 = FNot \psi 2$ 
  then obtain  $\psi 2$  where  $\varphi 2 = FNot \psi 2$  by metis
  hence only-c-inside  $c \varphi 2$ 
    by (metis all-subformula-st-def assms(1-3) connective.distinct(38,40) inc $\varphi 2$ 
      only-c-inside-decomp-not simple-not simple-not-def simple-not-symb.simps(1))
}
moreover {
  assume simple  $\varphi 2$ 
  hence only-c-inside  $c \varphi 2$ 
    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 $\varphi 2$ : only-c-inside  $c \varphi 2$  by metis
show ?case using l only-c-inside $\varphi 1$  only-c-inside $\varphi 2$  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* [φ , ψ]
 \Rightarrow *grouped-by* *c* (*conn* *c* [φ , ψ])

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'*:

$only-c-inside-symb\ c\ (conn\ c'\ [\varphi 1, \varphi 2]) \implies c' = CAnd \vee c' = COr \implies wf-conn\ c'\ [\varphi 1, \varphi 2]$
 $\implies c' = c$
by (induct conn c' $[\varphi 1, \varphi 2]$ rule: *only-c-inside-symb.induct*, auto simp add: *conn-inj*)

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

$only-c-inside\ c\ (conn\ c'\ [\varphi 1, \varphi 2]) \implies c' = CAnd \vee c' = COr \implies wf-conn\ c'\ [\varphi 1, \varphi 2] \implies c = c'$
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 $c: c \neq CNot$ **and** $c': c' = CAnd \vee c' = COr$
shows $only-c-inside\ c\ \varphi \implies grouped-by\ c\ \varphi$ (**is** $?O\ \varphi \implies ?G\ \varphi$)

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

case (*nullary* $\varphi\ x$)

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

next

case (*unary* ψ)

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

next

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

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

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

proof –

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

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* $\varphi-c''\ l''$ **by** *metis*

hence $c = c''$

by (*metis* $\varphi\ \varphi-c''\ conn-inj\ conn-inj-not(2)\ l''\ list.distinct(1)\ list.inject\ wf$

only-c-inside-symb.cases simple.simps(5-8))

thus $\varphi = conn\ c\ [\varphi 1, \varphi 2]$ **and** $wf-conn\ c\ [\varphi 1, \varphi 2]$ **using** $\varphi-c''\ wf\ l''$ **by** *auto*

qed

have $grouped-by\ c\ \varphi 1$ **using** $wf\ IH\varphi 1\ IH\varphi 2\ \varphi-conn\ only\ \varphi$ **unfolding** *only-c-inside-def* **by** *auto*

moreover **have** $grouped-by\ c\ \varphi 2$

using $wf\ \varphi\ IH\varphi 1\ IH\varphi 2\ \varphi-conn\ only$ **unfolding** *only-c-inside-def* **by** *auto*

ultimately show $?G\ \varphi$ **using** $\varphi-conn\ connected-is-group\ local.wf$ **by** *blast*

qed

lemma *grouped-by-false*:

$grouped-by\ c\ (conn\ c'\ [\varphi, \psi]) \implies c \neq c' \implies wf-conn\ c'\ [\varphi, \psi] \implies False$

apply (induct conn c' $[\varphi, \psi]$ 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* \Rightarrow ' a *connective* \Rightarrow ' a *propo* \Rightarrow *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: $super-grouped-by\ c\ c'\ \varphi \implies super-grouped-by\ c\ c'\ \psi \implies wf-conn\ c\ [\varphi, \psi]$
 $\implies super-grouped-by\ c\ c'\ (conn\ c'\ [\varphi, \psi])$

```

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  $\vee$  c = COr and c': c' = CAnd  $\vee$  c' = COr and cc': c  $\neq$  c'
  shows no-equiv  $\varphi \implies$  no-imp  $\varphi \implies$  simple-not  $\varphi \implies$  c-in-c'-only c c'  $\varphi$ 
     $\implies$  super-grouped-by c c'  $\varphi$ 
    (is ?NE  $\varphi \implies$  ?NI  $\varphi \implies$  ?SN  $\varphi \implies$  ?C  $\varphi \implies$  ?S  $\varphi$ )
proof (induct  $\varphi$  rule: propo-induct-arity)
  case (nullary  $\varphi$  x)
  thus ?S  $\varphi$  by auto
next
  case (unary  $\varphi$ )
  hence simple-not-symb (FNot  $\varphi$ )
    using all-subformula-st-test-symb-true-phi unfolding simple-not-def by blast
  hence  $\varphi = FT \vee \varphi = FF \vee (\exists x. \varphi = FVar\ x)$  by (cases  $\varphi$ , auto)
  thus ?S (FNot  $\varphi$ ) by auto
next
  case (binary  $\varphi$   $\varphi1$   $\varphi2$ )
  note IH $\varphi1 = this(1)$  and IH $\varphi2 = this(2)$  and no-equiv = this(4) and no-imp = this(5)
    and simpleN = this(6) and c-in-c'-only = this(7) and  $\varphi' = this(3)$ 
  {
    assume  $\varphi = FImp\ \varphi1\ \varphi2 \vee \varphi = FEq\ \varphi1\ \varphi2$ 
    hence False using no-equiv no-imp by auto
    hence ?S  $\varphi$  by auto
  }
  moreover {
    assume  $\varphi$ :  $\varphi = conn\ c'\ [\varphi1, \varphi2] \wedge wf\text{-}conn\ c'\ [\varphi1, \varphi2]$ 
    have c-in-c'-only: c-in-c'-only c c'  $\varphi1 \wedge c\text{-in-}c'\text{-only}$  c c'  $\varphi2 \wedge c\text{-in-}c'\text{-symb}$  c c'  $\varphi$ 
      using c-in-c'-only  $\varphi'$  unfolding c-in-c'-only-def by auto
    have super-grouped-by c c'  $\varphi1$  using  $\varphi\ c'$  no-equiv no-imp simpleN IH $\varphi1$  c-in-c'-only by auto
    moreover have super-grouped-by c c'  $\varphi2$ 
      using  $\varphi\ c'$  no-equiv no-imp simpleN IH $\varphi2$  c-in-c'-only by auto
    ultimately have ?S  $\varphi$ 
      using super-grouped-by.intros(2)  $\varphi$  by (metis c wf-conn-helper-facts(5,6))
  }
  moreover {
    assume  $\varphi$ :  $\varphi = conn\ c\ [\varphi1, \varphi2] \wedge wf\text{-}conn\ c\ [\varphi1, \varphi2]$ 
    hence only-c-inside c  $\varphi1 \wedge only\text{-}c\text{-inside}$  c  $\varphi2$ 
      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  $[\varphi1, \varphi2]$ )
      unfolding only-c-inside-def using  $\varphi$ 
      by (simp add: only-c-inside-into-only-c-inside all-subformula-st-decomp)
    hence grouped-by c  $\varphi$  using  $\varphi$  only-c-inside-imp-grouped-by c by blast
    hence ?S  $\varphi$  using super-grouped-by.intros(1) by metis
  }

```

ultimately show $?S \varphi$ by (metis $\varphi' c c' cc' \text{conn.simps}(5,6) \text{wf-conn-helper-facts}(5,6)$)
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* $\varphi \implies \text{no-imp } \varphi \implies \text{simple-not } \varphi \implies \text{or-in-and-only } \varphi \implies \text{is-conj-with-TF } \varphi$
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* $\varphi == \text{is-conj-with-TF } \varphi \wedge \text{no-T-F-except-top-level } \varphi$

9.2.1 Full CNF transformation

The full1 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* $\varphi \varphi' \implies \text{is-cnf } \varphi'$

apply (*unfold cnf-rew-def OO-def*)
apply *auto*

proof –

fix $\varphi \varphi \text{Eq } \varphi \text{Imp } \varphi \text{TB } \varphi \text{Neg } \varphi \text{Disj} :: 'v \text{ propo}$
assume *Eq*: *full (propo-rew-step elim-equiv)* $\varphi \varphi \text{Eq}$
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)* $\varphi \text{Eq } \varphi \text{Imp}$
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)* $\varphi \text{Imp } \varphi \text{TB}$
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)* $\varphi \text{TB } \varphi \text{Neg}$
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)* $\varphi \text{Neg } \varphi \text{Disj}$
hence *no-Disj*: *or-in-and-only* φDisj

using *noNeg-inv noNeg pushDisj-full-propo-rew-step* **by** *blast*
have *noDisj-inv: no-equiv φ Disj no-imp φ Disj no-T-F-except-top-level φ Disj*
simple-not φ Disj
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**

$ElimTBFull1[simp]: elimTBFull (FAnd \varphi FT) \varphi \mid$
 $ElimTBFull1'[simp]: elimTBFull (FAnd FT \varphi) \varphi \mid$

 $ElimTBFull2[simp]: elimTBFull (FAnd \varphi FF) FF \mid$
 $ElimTBFull2'[simp]: elimTBFull (FAnd FF \varphi) FF \mid$

 $ElimTBFull3[simp]: elimTBFull (FOr \varphi FT) FT \mid$
 $ElimTBFull3'[simp]: elimTBFull (FOr FT \varphi) FT \mid$

 $ElimTBFull4[simp]: elimTBFull (FOr \varphi FF) \varphi \mid$
 $ElimTBFull4'[simp]: elimTBFull (FOr FF \varphi) \varphi \mid$

 $ElimTBFull5[simp]: elimTBFull (FNot FT) FF \mid$
 $ElimTBFull5'[simp]: elimTBFull (FNot FF) FT \mid$

 $ElimTBFull6-l[simp]: elimTBFull (FImp FT \varphi) \varphi \mid$
 $ElimTBFull6-l'[simp]: elimTBFull (FImp FF \varphi) FT \mid$
 $ElimTBFull6-r[simp]: elimTBFull (FImp \varphi FT) FT \mid$
 $ElimTBFull6-r'[simp]: elimTBFull (FImp \varphi FF) (FNot \varphi) \mid$

 $ElimTBFull7-l[simp]: elimTBFull (FEq FT \varphi) \varphi \mid$
 $ElimTBFull7-l'[simp]: elimTBFull (FEq FF \varphi) (FNot \varphi) \mid$
 $ElimTBFull7-r[simp]: elimTBFull (FEq \varphi FT) \varphi \mid$
 $ElimTBFull7-r'[simp]: elimTBFull (FEq \varphi FF) (FNot \varphi) \mid$

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** $elimTBFULL.intros \text{ binary.hyps}(3)$ **by** $blast$
qed

The same applies here. We do not need the assumption, but the deep link between $\neg no-T-F-except-top-level \varphi$ and the existence of a rewriting step, still exists.

lemma $no-T-F-except-top-level-rew'$:
fixes $\varphi :: 'v \text{ propo}$
assumes $noTB: \neg no-T-F-except-top-level \varphi$
shows $\exists \psi \psi'. \psi \preceq \varphi \wedge elimTBFULL \psi \psi'$
proof –
have $test-symb-false-nullary$:
 $\forall x. no-T-F-symb-except-toplevel (FF:: 'v \text{ propo}) \wedge no-T-F-symb-except-toplevel FT$
 $\wedge no-T-F-symb-except-toplevel (FVar (x:: 'v))$
by $auto$
moreover {
fix $c:: 'v \text{ connective}$ **and** $l:: 'v \text{ propo list}$ **and** $\psi:: 'v \text{ propo}$
have $H: elimTBFULL (conn c l) \psi \implies \neg no-T-F-symb-except-toplevel (conn c l)$
by $(cases (conn c l) rule: elimTBFULL.cases) auto$
}
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 $propo-rew-step-ElimEquiv-no-T-F$: $propo-rew-step elim-equiv \varphi \psi \implies no-T-F \varphi \implies no-T-F \psi$

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 $\forall x0 x1. (\neg elim-equiv (x1 :: 'v \text{ propo}) x0 \vee (\exists v2 v3 v4 v5 v6 v7. x1 = FEq v2 v3$
 $\wedge x0 = FAnd (FImp v4 v5) (FImp v6 v7) \wedge v2 = v4 \wedge v4 = v7 \wedge v3 = v5 \wedge v3 = v6))$
 $= (\neg elim-equiv x1 x0 \vee (\exists v2 v3 v4 v5 v6 v7. x1 = FEq v2 v3$
 $\wedge x0 = FAnd (FImp v4 v5) (FImp v6 v7) \wedge v2 = v4 \wedge v4 = v7 \wedge v3 = v5 \wedge v3 = v6))$

by $meson$

hence $\forall p pa. \neg elim-equiv (p :: 'v \text{ propo}) pa \vee (\exists pb pc pd pe pf pg. p = FEq pb pc$
 $\wedge pa = FAnd (FImp pd pe) (FImp pf pg) \wedge pb = pd \wedge pd = pg \wedge pc = pe \wedge pc = pf)$

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  $\varphi \implies$  no-T-F  $\varphi'$ 
and corr: wf-conn c ( $\xi @ \varphi \# \xi'$ )
and no-T-F: no-T-F (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  $\zeta \ \varphi'$  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  $\varphi' \ l'$  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  $l'$  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  $\varphi$ 
  shows no-T-F-except-top-level  $\psi$ 
proof -
  {
    fix  $\varphi \ \psi :: 'v \text{ propo}$ 
    have propo-rew-step elim-equiv  $\varphi \ \psi \implies$  no-T-F-except-top-level  $\varphi$ 
       $\implies$  no-T-F-except-top-level  $\psi$ 
    proof -
      assume rel: propo-rew-step elim-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  $\xi \xi' :: 'v \text{propo list}$  and  $\zeta \zeta' :: 'v \text{propo}$ 
  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  $c$ :  $c \in \text{binary-connectives}$ 
  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  $\zeta$ :  $\forall \zeta \in \text{set } (\xi @ \varphi \# \xi'). \text{no-T-F } \zeta$  using  $ab$   $c$  propo-rew-one-step-lift.prem 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  $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi'). \text{no-T-F } \zeta$  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  $H = \text{this}$ 
    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-rew'* :: '*a* *propo* \Rightarrow '*a* *propo* \Rightarrow *bool* **where** *dnf-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 50) where*

$$I \models_l L \longleftrightarrow L \in I$$

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*:
 $a \notin A \implies \neg a \notin A \implies \text{consistent-interp } (\text{insert } (\neg a) A) \longleftrightarrow \text{consistent-interp } (\text{insert } a A)$
unfolding *consistent-interp-def* **by** *fastforce*

lemma *consistent-interp-insert-pos*[*simp*]:
 $a \notin A \implies \text{consistent-interp } (\text{insert } a A) \longleftrightarrow \text{consistent-interp } A \wedge \neg a \notin A$
unfolding *consistent-interp-def* **by** *auto*

lemma *consistent-interp-insert-not-in*:
consistent-interp $A \implies a \notin A \implies \neg a \notin A \implies \text{consistent-interp } (\text{insert } a A)$
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-msultiset*[*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*:
 $A \subseteq B \implies \text{atms-of-ms } A \subseteq \text{atms-of-ms } B$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-finite[simp]*:
 $\text{finite } \psi s \implies \text{finite } (\text{atms-of-ms } \psi s)$
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]*:
 $\text{atms-of-ms } (\text{insert } \psi s \chi s) = \text{atms-of-ms } \psi s \cup \text{atms-of-ms } \chi s$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-singleton[simp]*: $\text{atms-of-ms } \{L\} = \text{atms-of-ms } L$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-atms-of-ms-mono[simp]*:
 $A \in \psi \implies \text{atms-of-ms } A \subseteq \text{atms-of-ms } \psi$
unfolding *atms-of-ms-def* **by** *fastforce*

lemma *atms-of-ms-single-set-mset-atms-of[simp]*:
 $\text{atms-of-ms } (\text{single } ' \text{ set-mset } B) = \text{atms-of-ms } B$
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 $\text{in-implies-atm-of-on-atms-of-ms[of } C + \{\#L\# \}] \text{ assms by auto}$

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]*:

total-over-set I (*insert* L Ls) $\longleftrightarrow ((Pos\ L \in I \vee Neg\ L \in I) \wedge total-over-set\ I\ Ls)$
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*) (*rename-tac* L , *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 $A \in I \vee -A \in I$
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 $L: \neg L \in \# \psi - L \notin \# \psi$
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 $L \in \# \psi \vee -L \in \# \psi$ **by** (*cases 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* $I \psi$
shows *total-over-m* $(I \cup I') \psi$
using *assms unfolding total-over-m-def total-over-set-def* **by** *auto*

lemma *total-union-2*:
assumes *total-over-m* $I \psi$
and *total-over-m* $I' \psi'$
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**
 $I \models C \longleftrightarrow (\exists L \in \# C. I \models L)$

lemma *true-cls-empty[iff]*: $\neg I \models \{\#\}$
unfolding *true-cls-def* **by** *auto*

lemma *true-cls-singleton[iff]*: $I \models \{\#L\# \} \longleftrightarrow I \models L$
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]*: $A \subseteq\# B \implies I \models A \implies I \models B$
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-def* **by** *auto*
let $?I = \{P. P \in I \wedge atm\text{-}of\ P \in atms\text{-}of\text{-}ms\ CC\}$

have $I \text{-} CC: ?I \models_s CC$
using $I \text{-} CC$ *in-implies-atm-of-on-atms-of-ms* **unfolding** *true-clss-def Ball-def true-cls-def Bex-mset-def true-lit-def*
by *blast*

moreover have $cons: consistent\text{-}interp\ ?I$
using $cons$ **unfolding** *consistent-interp-def* **by** *auto*
moreover have $total\text{-}over\text{-}m\ ?I\ CC$
using tot **unfolding** *total-over-m-def total-over-set-def* **by** *auto*
moreover
have $atms\text{-}CC\text{-}incl: atms\text{-}of\text{-}ms\ CC \subseteq atm\text{-}of\ ?I$
using tot **unfolding** *total-over-m-def total-over-set-def atms-of-ms-def*
by (*auto simp add: atms-of-def atms-of-s-def[symmetric]*)
have $atm\text{-}of\ ' ?I = atms\text{-}of\text{-}ms\ CC$
using $atms\text{-}CC\text{-}incl$ **unfolding** *atms-of-ms-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-cls-mset-def* **by** *auto*

lemma $true\text{-}cls\text{-}mset\text{-}singleton[iff]: I \models_m \{\#C\# \} \longleftrightarrow I \models C$
unfolding *true-cls-mset-def* **by** (*auto split: split-if-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-cls-mset-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-cls-mset-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-cls-mset-def subset-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-clss-def true-cls-mset-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-cls-mset-def* **by** *auto*

theorem *true-cls-remove-unused*:

assumes $I \models \psi$
shows $\{v \in I. \text{atm-of } v \in \text{atms-of } \psi\} \models \psi$
using *assms unfolding true-cls-def atms-of-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-cls-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-cls-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-cls-remove-unused II'* **by** *blast*
moreover have $?I \subseteq I$ **using** H **by** *auto*
ultimately show $?thesis$ **using** *true-cls-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*: $\text{atms-of-s } A \cap \text{atms-of-s } I = \{\}$
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 ψ
  shows total-over-m {v ∈ I. atm-of v ∈ atms-of-ms ψ} ψ
  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' ⊨ D
  and atm-of a ∉ atms-of D
  shows M' ⊨ 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 interp and K :: 'v set
  shows total-over-set I K ⟷ (∀ l ∈ K. l ∈ (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* (ψ): $\text{'v clause} \equiv \forall I. \text{total-over-set } I (\text{atms-of } \psi) \longrightarrow I \models \psi$

```

lemma tautology-Pos-Neg[intro]:
  assumes Pos p ∈# A and Neg p ∈# 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 ∈# A and  $\neg L \in \# A$ 
  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 (atms-of ψ)
    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 (rename-tac  $x L$ , case-tac  $L$ ) fastforce+
  ultimately show False using assms unfolding tautology-def by auto
qed

```

```

lemma tautology-decomp:
  tautology ψ ⟷ (∃ p. Pos p ∈# ψ ∧ Neg p ∈# ψ)
  using tautology-exists-Pos-Neg by auto

```

```

lemma tautology-false[simp]:  $\neg \text{tautology } \{\#\}$ 
  unfolding tautology-def by auto

lemma tautology-add-single:
   $\text{tautology } (\{\#a\# \} + L) \longleftrightarrow \text{tautology } L \vee -a \in\# L$ 
  unfolding tautology-decomp by (cases a) auto

lemma minus-interp-tautology:
  assumes  $\{-L \mid L. L \in\# \chi\} \models \chi$ 
  shows tautology  $\chi$ 
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  $I \models \varphi \vee \text{tautology } \varphi$ 
  using assms unfolding true-cls-def by auto

lemma tautology-imp-tautology:
  fixes  $\chi \chi' :: 'v \text{ clause}$ 
  assumes  $\forall I. \text{total-over-m } I \ \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models \chi'$  and tautology  $\chi$ 
  shows tautology  $\chi'$  unfolding tautology-def
proof (intro allI HOL.impI)
  fix  $I :: 'v \text{ literal set}$ 
  assume totI: total-over-set  $I$  (atms-of  $\chi'$ )
  let  $?I' = \{Pos\ v \mid v. v \in \text{atms-of } \chi \wedge v \notin \text{atms-of-s } I\}$ 
  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* :: $'a \text{ clause} \Rightarrow 'a \text{ clause} \Rightarrow \text{bool}$ (**infix** \models_f 49) **where**
 $\psi \models_f \chi \longleftrightarrow (\forall I. \text{total-over-m } I \ (\{\psi\} \cup \{\chi\}) \longrightarrow \text{consistent-interp } I \longrightarrow I \models \psi \longrightarrow I \models \chi)$

definition *true-cls-clss* :: $'a \text{ clause} \Rightarrow 'a \text{ clauses} \Rightarrow \text{bool}$ (**infix** \models_{fs} 49) **where**
 $\psi \models_{fs} \chi \longleftrightarrow (\forall I. \text{total-over-m } I \ (\{\psi\} \cup \chi) \longrightarrow \text{consistent-interp } I \longrightarrow I \models \psi \longrightarrow I \models_s \chi)$

definition *true-clss-cls* :: $'a \text{ clauses} \Rightarrow 'a \text{ clause} \Rightarrow \text{bool}$ (**infix** \models_p 49) **where**
 $N \models_p \chi \longleftrightarrow (\forall I. \text{total-over-m } I \ (N \cup \{\chi\}) \longrightarrow \text{consistent-interp } I \longrightarrow I \models_s N \longrightarrow I \models \chi)$

definition *true-clss-clss* :: $'a \text{ clauses} \Rightarrow 'a \text{ clauses} \Rightarrow \text{bool}$ (**infix** \models_{ps} 49) **where**
 $N \models_{ps} N' \longleftrightarrow (\forall I. \text{total-over-m } I \ (N \cup N') \longrightarrow \text{consistent-interp } I \longrightarrow I \models_s N \longrightarrow I \models_s N')$

lemma *true-cls-cls-refl[simp]*:
 $A \models_f A$
unfolding *true-cls-cls-def* **by** *auto*

lemma *true-cls-cls-insert-l[simp]*:
 $a \models_f C \implies \text{insert } a \ A \models_p C$
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-clss-insert-l[simp]:
   $A \models_p C \implies \text{insert } a \ A \models_p C$ 
  unfolding true-clss-clss-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]:
   $A \models_{ps} C \cup D \longleftrightarrow (A \models_{ps} C \wedge A \models_{ps} D)$ 
proof
{
  fix  $A \ C \ D :: 'a \ \text{clauses}$ 
  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:  $\text{total-over-m } I \ (A \cup C)$ 
      and cons: consistent-interp  $I$ 
      and  $I: I \models_s A$ 
      then have tot:  $\text{total-over-m } I \ A$  and tot':  $\text{total-over-m } I \ C$  by auto
      obtain  $I'$  where tot':  $\text{total-over-m } (I \cup I') \ (A \cup C \cup D)$ 
      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 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  $H = \text{this}$ 
  assume  $A \models_{ps} C \cup D$ 
  then show  $A \models_{ps} C \wedge A \models_{ps} D$  using  $H[\text{of } A] \ \text{Un-commute}[\text{of } C \ D]$  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]:
   $A \models_{ps} \text{insert } L \ Ls \longleftrightarrow (A \models_p L \wedge A \models_{ps} Ls)$ 
  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:  $B \models_{ps} C$ 
  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  $\langle \text{consistent-interp } I \rangle$  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-cla-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-cla-def by auto
  }
ultimately show  $I \models D + C$  by blast
qed

```

lemma *true-cla-union-mset[iff]*: $I \models C \# \cup D \longleftrightarrow I \models C \vee I \models D$
unfolding true-cla-def by *force*

lemma *true-clss-cla-union-mset-true-clss-cla-or-not-true-clss-cla-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-cla-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-cla-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-cla-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  $?I' \models N$  using  $\langle I \models N \rangle$  using true-clss-union-increase by blast
  ultimately have  $?I' \models D + \{\# - L\# \}$ 
    using  $D$  unfolding true-clss-cl-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-cl-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 $I: I \models s \varphi$ bymetis

let $?I' = \{ \text{Pos } v \mid v. v \notin \text{atms-of-s } I \wedge v \in \text{atms-of-ms } \varphi \}$

have consistent-interp $(I \cup ?I')$

using *cons* unfolding consistent-interp-def by (intro allI) (rename-tac L , 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-cl-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 bymetis

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 *atms-of-replicate-mset-replicate-mset-uminus[simp]*:

atms-of $(D - \text{replicate-mset } (\text{count } D L) L - \text{replicate-mset } (\text{count } D (-L)) (-L))$

= 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 $\{ \text{Pos } v \mid v. v \in \text{atms-of } D \wedge v \notin \text{atms-of } C \}$ arbitrary: D)

```

  rule: nat-less-induct-case)
case 0 note  $n = \text{this}(1)$  and  $H = \text{this}(2)$  and  $\text{incl} = \text{this}(3)$ 
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  $\text{incl true-cl-}m\text{-}l\text{-}eD$  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  $\text{incl} = \text{this}(4)$ 
let ?atms =  $\{ \text{Pos } v \mid v. v \in \text{atms-of } D \wedge v \notin \text{atms-of } C \}$ 
have finite ?atms by auto
then obtain  $L$  where  $L: L \in ?\text{atms}$ 
  using  $\text{card}$  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  $\text{tot}: \text{total-over-}m \ (I \cup \{L\}) \ \{D\}$ 
    unfolding total-over- $m$ -def total-over-set-def using  $\text{atms-of-}D$  by auto

  assume  $IDL: I \models ?D'$ 
  then have  $I \cup \{L\} \models D$  unfolding true-cl- $s$ -def by force
  then have  $I \cup \{L\} \models \varphi$  using  $H \ \text{tot}$  by auto

  moreover
  have  $\text{tot}': \text{total-over-}m \ (I \cup \{-L\}) \ \{D\}$ 
    using  $\text{tot}$  unfolding total-over- $m$ -def total-over-set-def by auto
  have  $I \cup \{-L\} \models D$  using  $IDL$  unfolding true-cl- $s$ -def by force
  then have  $I \cup \{-L\} \models \varphi$  using  $H \ \text{tot}'$  by auto
  ultimately have  $I \models \varphi \vee \text{tautology } \varphi$ 
    using  $L \ \text{remove-literal-in-model-tautology}$  by force
} note  $H' = \text{this}$ 

have  $L \notin \# \ C$  and  $-L \notin \# \ C$  using  $L \ \text{atm-iff-pos-or-neg-lit}$  by force+
then have  $C\text{-in-}D': C \subseteq \# \ ?D' \text{ using } \langle C \subseteq \# \ D \rangle$  by (auto simp add: subseteq-mset-def)
have  $\text{card } \{ \text{Pos } v \mid v. v \in \text{atms-of } ?D' \wedge v \notin \text{atms-of } C \} <$ 
   $\text{card } \{ \text{Pos } v \mid v. v \in \text{atms-of } D \wedge v \notin \text{atms-of } C \}$ 
  using  $L$  by (auto intro!: psubset-card-mono)
then show ?case
  using  $IH \ C\text{-in-}D' \ H'$  unfolding  $\text{card}[\text{symmetric}]$  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]*: $\text{atms-of } (\text{remdups-mset } C) = \text{atms-of } C$

unfolding atms-of-def by auto

lemma *true-cl-remdups-mset[iff]*: $I \models \text{remdups-mset } C \longleftrightarrow I \models C$

unfolding true-cl- s -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

definition *simple-clss* :: '*v* set \Rightarrow '*v* clause set **where**
simple-clss *atms* = $\{C. \text{atms-of } C \subseteq \text{atms} \wedge \neg \text{tautology } C \wedge \text{distinct-mset } C\}$

lemma *simple-clss-empty*[simp]:
simple-clss $\{\}$ = $\{\{\#\}\}$
unfolding *simple-clss-def* **by** *auto*

lemma *simple-clss-insert*:
assumes $l \notin \text{atms}$
shows *simple-clss* (*insert* l *atms*) =
 $(\text{op} + \{\#\text{Pos } l\}) \cdot (\text{simple-clss } \text{atms})$
 $\cup (\text{op} + \{\#\text{Neg } l\}) \cdot (\text{simple-clss } \text{atms})$
 $\cup \text{simple-clss } \text{atms}(\text{is } ?I = ?U)$

proof (*standard*; *standard*)

fix C
assume $C \in ?I$
then have
 $\text{atms: } \text{atms-of } C \subseteq \text{insert } l \text{ atms}$ **and**
 $\text{taut: } \neg \text{tautology } C$ **and**
 $\text{dist: } \text{distinct-mset } C$
unfolding *simple-clss-def* **by** *auto*
have $H: \bigwedge x. x \in \# C \implies \text{atm-of } x \in \text{insert } l \text{ atms}$
using *atm-of-lit-in-atms-of atms* **by** *blast*
consider
 $(\text{Add}) \ L \text{ where } L \in \# C \text{ and } L = \text{Neg } l \vee L = \text{Pos } l$
 $| (\text{No}) \ \text{Pos } l \notin \# C \ \text{Neg } l \notin \# C$
by *auto*

then show $C \in ?U$

proof *cases*

case *Add*

then have $L \notin \# C - \{\#L\}$

using *dist* **unfolding** *distinct-mset-def* **by** *auto*

moreover have $-L \notin \# C$

using *taut Add* **by** *auto*

ultimately have $\text{atms-of } (C - \{\#L\}) \subseteq \text{atms}$

using *atms Add* **by** (*auto simp: atm-iff-pos-or-neg-lit split: split-if-asm dest!: H*)

moreover have $\neg \text{tautology } (C - \{\#L\})$

using *taut* **by** (*metis Add(1) insert-DiffM tautology-add-single*)

moreover have $\text{distinct-mset } (C - \{\#L\})$

using *dist* **by** *auto*

ultimately have $(C - \{\#L\}) \in \text{simple-clss } \text{atms}$

using *Add* **unfolding** *simple-clss-def* **by** *auto*

moreover have $C = \{\#L\} + (C - \{\#L\})$

using *Add* **by** (*auto simp: multiset-eq-iff*)

ultimately show *thesis* **using** *Add* **by** *auto*

next

case *No*

then have $C \in \text{simple-clss } \text{atms}$

using *taut atms dist* **unfolding** *simple-clss-def*

```

    by (auto simp: atm-iff-pos-or-neg-lit split: split-if-asm dest!: H)
  then show ?thesis by blast
qed
next
fix C
assume C ∈ ?U
then consider
  (Add) L C' where C = {#L#} + C' and C' ∈ simple-clss atms and
    L = Pos l ∨ L = Neg l
  | (No) C ∈ simple-clss atms
by auto
then show C ∈ ?I
proof cases
case No
  then show ?thesis unfolding simple-clss-def by auto
next
case (Add L C') note C' = this(1) and C = this(2) and L = this(3)
  then have
    atms: atms-of C' ⊆ atms and
    taut: ¬tautology C' and
    dist: distinct-mset C'
    unfolding simple-clss-def by auto
  have atms-of C ⊆ insert l atms
    using atms C' L by auto
  moreover have ¬tautology C
    using taut C' L by (metis assms atm-of-lit-in-atms-of atms literal.sel(1,2) subset-eq
      tautology-add-single uminus-Neg uminus-Pos)
  moreover have distinct-mset C
    using dist C' L
    by (metis assms atm-of-lit-in-atms-of atms contra-subsetD distinct-mset-add-single
      literal.sel(1,2))
  ultimately show ?thesis unfolding simple-clss-def by blast
qed
qed

```

lemma *simple-clss-finite*:

```

fixes atms :: 'v set
assumes finite atms
shows finite (simple-clss atms)
using assms by (induction rule: finite-induct) (auto simp: simple-clss-insert)

```

lemma *simple-clssE*:

```

assumes
  x ∈ simple-clss atms
shows atms-of x ⊆ atms ∧ ¬tautology x ∧ distinct-mset x
using assms unfolding simple-clss-def by auto

```

lemma *cls-in-simple-clss*:

```

shows {#} ∈ simple-clss s
unfolding simple-clss-def by auto

```

lemma *simple-clss-card*:

```

fixes atms :: 'v set
assumes finite atms
shows card (simple-clss atms) ≤ (3::nat) ^ (card atms)

```

```

using assms
proof (induct atms rule: finite-induct)
  case empty
  then show ?case by auto
next
case (insert l C) note fin = this(1) and l = this(2) and IH = this(3)
have notin:
   $\wedge C'. \{\#Pos\ l\#\} + C' \notin \text{simple-clss } C$ 
   $\wedge C'. \{\#Neg\ l\#\} + C' \notin \text{simple-clss } C$ 
  using l unfolding simple-clss-def by auto
have H:  $\wedge C' D. \{\#Pos\ l\#\} + C' = \{\#Neg\ l\#\} + D \implies D \in \text{simple-clss } C \implies \text{False}$ 
proof -
  fix C' D
  assume C'D:  $\{\#Pos\ l\#\} + C' = \{\#Neg\ l\#\} + D$  and D:  $D \in \text{simple-clss } C$ 
  then have Pos l  $\in \#$  D by (metis insert-noteq-member literal.distinct(1) union-commute)
  then have l  $\in$  atms-of D
    by (simp add: atm-iff-pos-or-neg-lit)
  then show False using D l unfolding simple-clss-def by auto
qed
let ?P = (op +  $\{\#Pos\ l\#\}$ ) ' (simple-clss C)
let ?N = (op +  $\{\#Neg\ l\#\}$ ) ' (simple-clss C)
let ?O = simple-clss C
have card (?P  $\cup$  ?N  $\cup$  ?O) = card (?P  $\cup$  ?N) + card ?O
  apply (subst card-Un-disjoint)
  using l fin by (auto simp: simple-clss-finite notin)
moreover have card (?P  $\cup$  ?N) = card ?P + card ?N
  apply (subst card-Un-disjoint)
  using l fin H by (auto simp: simple-clss-finite notin)
moreover
  have card ?P = card ?O
    using inj-on-iff-eq-card[of ?O op +  $\{\#Pos\ l\#\}$ ]
    by (auto simp: fin simple-clss-finite inj-on-def)
  moreover have card ?N = card ?O
    using inj-on-iff-eq-card[of ?O op +  $\{\#Neg\ l\#\}$ ]
    by (auto simp: fin simple-clss-finite inj-on-def)
  moreover have  $(3::nat) \wedge \text{card (insert l C)} = 3 \wedge (\text{card } C) + 3 \wedge (\text{card } C) + 3 \wedge (\text{card } C)$ 
    using l by (simp add: fin mult-2-right numeral-3-eq-3)
  ultimately show ?case using IH l by (auto simp: simple-clss-insert)
qed

```

```

lemma simple-clss-mono:
  assumes incl:  $\text{atms} \subseteq \text{atms}'$ 
  shows simple-clss  $\text{atms} \subseteq \text{simple-clss } \text{atms}'$ 
  using assms unfolding simple-clss-def by auto

```

```

lemma distinct-mset-not-tautology-implies-in-simple-clss:
  assumes distinct-mset  $\chi$  and  $\neg \text{tautology } \chi$ 
  shows  $\chi \in \text{simple-clss (atms-of } \chi)$ 
  using assms unfolding simple-clss-def by auto

```

```

lemma simplified-in-simple-clss:
  assumes distinct-mset-set  $\psi$  and  $\forall \chi \in \psi. \neg \text{tautology } \chi$ 
  shows  $\psi \subseteq \text{simple-clss (atms-of-ms } \psi)$ 
  using assms unfolding simple-clss-def
  by (auto simp: distinct-mset-set-def atms-of-ms-def)

```

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]:  $I \neq \{\}$   $\Rightarrow$   $\text{insert } L \ I \models_e x \longleftrightarrow \{L\} \models_e x \vee I \models_e x$ 
  assumes entail-union[simp]:  $I \models_e A \Rightarrow I \cup I' \models_e A$ 
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]:
   $M \models_{es} A \Rightarrow \text{insert } L \ M \models_{es} A$ 
  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:  $DD \subseteq CC \Rightarrow I \models_{es} CC \Rightarrow I \models_{es} DD$ 
  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]:  $I \models_{es} N \Rightarrow I \models_{es} \text{Set.remove } a \ N$ 
  by (simp add: entails-def)

lemma entails-remove-minus[simp]:  $I \models_{es} N \Rightarrow I \models_{es} N - A$ 
  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

```


$I \models_{\text{sext}} N \longleftrightarrow (\forall J. I \subseteq J \longrightarrow \text{consistent-interp } J \longrightarrow \text{total-over-m } J N \longrightarrow J \models_s N)$

lemma *true-clss-imp-true-clss-ext*:

$I \models_s N \implies I \models_{\text{sext}} N$

unfolding *true-clss-ext-def* **by** (*metis sup.orderE true-clss-union-increase*)

lemma *true-clss-ext-decrease-right-remove-r*:

assumes $I \models_{\text{sext}} N$

shows $I \models_{\text{sext}} N - \{C\}$

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** (*intro allI*)

by (*rename-tac L, case-tac L*) (*fastforce simp add: image-iff*)**+**

moreover have *total-over-m* $?J N$

using *tot* **unfolding** *total-over-m-def total-over-set-def atms-of-ms-def*

apply *clarify*

apply (*rename-tac l a, case-tac 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 simp: atms-of-def*)

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** $I \models_{\text{sext}} A$

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 $\neg \text{consistent-interp } I$

shows $I \models_{\text{sext}} A$

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:

$(A + \{\#Pos\ P\# \} + \{\#Neg\ P\# \}) \in N \implies simplify\ N\ (N - \{A + \{\#Pos\ P\# \} + \{\#Neg\ P\# \}\})$

condensation:

$(A + \{\#L\# \} + \{\#L\# \}) \in N \implies simplify\ N\ (N - \{A + \{\#L\# \} + \{\#L\# \}\} \cup \{A + \{\#L\# \}\})$

subsumption:

$A \in N \implies A \subset\# B \implies B \in N \implies simplify\ N\ (N - \{B\})$

lemma *simplify-preserves-un-sat'*:

fixes *N N'* :: 'v 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 $I \models_s N - \{B\} \implies I \models A$ **using** $\langle A \in N \rangle$ **by** (*simp add: true-clss-def*)

moreover have $I \models A \implies I \models B$ **using** $\langle A \subset\# B \rangle$ **by** *auto*

ultimately show ?case **by** (*metis insert-Diff-single true-clss-insert*)

qed

lemma *simplify-preserves-un-sat*:

fixes *N N'* :: 'v 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 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 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* $\psi \longleftrightarrow \text{finite } \psi'$
using *assms* **by** (*induct rule: simplify.induct*, *auto simp add: remove-def*)

lemma *rtranclp-simplify-preserves-finite*:
assumes *rtranclp simplify* $\psi \ \psi'$
shows *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 *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 $A + \{\#P\# \} + \{\#P\# \} \in \psi \implies \exists x \in \psi. \text{atm-of } P \in \text{atm-of 'set-mset } x$
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 *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 uncon-state* = *'v clauses*

inductive *uncon-res* :: *'v uncon-state* \Rightarrow *'v uncon-state* \Rightarrow *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 *rtrancpl-uncon-inference-increasing*:
assumes *rtrancpl uncon-res* S S' **and** $\psi \in S$
shows $\psi \in S'$
using *assms* **by** (*induct rule: rtrancpl-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 $\chi' \longleftrightarrow$
 $(\forall I. \text{total-over-}m\ I\ \{\chi'\} \longrightarrow \text{total-over-}m\ I\ \{\chi\})$
 $\wedge (\forall I. \text{total-over-}m\ I\ \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models \chi')$

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*)
 $\Longrightarrow \text{inference } S (\text{fst } S \cup \{\text{clause}\}, \text{already-used})$

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 ( $\text{fst } S \cup \{\text{fst } S'\}$ ,  $\text{snd } S'$ )
  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 ( $N$ , already-used)
  shows already-used-inv ( $N'$ , 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  $A :: 'a \text{ set}$  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  $a \ a0 :: 'v \text{ clause}$  and  $A :: 'v \text{ clauses}$  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
   $q: (\exists \chi \in N. \text{subsumes } \chi (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
   $\vee \text{tautology } (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
using  $\text{inv } x$  by  $\text{fastforce}$ 
consider  $(\text{taut}) \text{tautology } (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \}))) \mid$ 
   $(\chi) \chi$  where  $\chi \in N$   $\text{subsumes } \chi (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
   $\neg \text{tautology } (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
using  $q$  by  $\text{auto}$ 
then show
   $\exists p. \text{Pos } p \in\# a \wedge \text{Neg } p \in\# b$ 
   $\wedge ((\exists \chi \in \text{fst } (N - \{B\}, \text{already-used}). \text{subsumes } \chi (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
   $\vee \text{tautology } (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
proof cases
  case  $\text{taut}$ 
    then show  $?thesis$  using  $p$  by  $\text{auto}$ 
  next
    case  $\chi$  note  $H = \text{this}$ 
    show  $?thesis$  using  $p$   $A$   $AB$   $B$   $\text{subsumes-subsumption}[OF - AB\ H(3)]\ H(1,2)$  by  $\text{auto}$ 
  qed
qed
next
case  $(\text{tautology-deletion } C\ P)$ 
then show  $?case$  apply  $\text{clarify}$ 
proof  $-$ 
  fix  $a\ b$ 
assume  $C + \{\#Pos\ P\# \} + \{\#Neg\ P\# \} \in N$ 
assume  $\text{already-used-inv } (N, \text{already-used})$ 
and  $(a, b) \in \text{snd } (N - \{C + \{\#Pos\ P\# \} + \{\#Neg\ P\# \}\}, \text{already-used})$ 
then obtain  $p$  where
   $\text{Pos } p \in\# a \wedge \text{Neg } p \in\# b \wedge$ 
   $((\exists \chi \in \text{fst } (N \cup \{C + \{\#Pos\ P\# \} + \{\#Neg\ P\# \}\}, \text{already-used}).$ 
   $\text{subsumes } \chi (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
   $\vee \text{tautology } (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
  by  $\text{fastforce}$ 
moreover have  $\text{tautology } (C + \{\#Pos\ P\# \} + \{\#Neg\ P\# \})$  by  $\text{auto}$ 
ultimately show
   $\exists p. \text{Pos } p \in\# a \wedge \text{Neg } p \in\# b$ 
   $\wedge ((\exists \chi \in \text{fst } (N - \{C + \{\#Pos\ P\# \} + \{\#Neg\ P\# \}\}, \text{already-used}).$ 
   $\text{subsumes } \chi (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
   $\vee \text{tautology } (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$ 
  by  $(\text{metis } (\text{no-types})\ \text{Diff-iff}\ \text{Un-insert-right}\ \text{empty-iff}\ \text{fst-conv}\ \text{insertE}\ \text{subsumes-tautology}$ 
   $\text{sup-bot.right-neutral})$ 
qed
qed

```

lemma

factoring-satisfiable: $I \models \{\#L\# \} + \{\#L\# \} + C \longleftrightarrow I \models \{\#L\# \} + C$ **and**

resolution-satisfiable:

consistent-interp $I \implies I \models \{\#Pos\ p\# \} + C \implies I \models \{\#Neg\ p\# \} + D \implies I \models C + D$ **and**

factoring-same-vars: $\text{atms-of } (\{\#L\# \} + \{\#L\# \} + C) = \text{atms-of } (\{\#L\# \} + C)$

unfolding *true-cls-def consistent-interp-def* **by** $(\text{fastforce split: split-if-asm})+$

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 *rtrancp-inference-increasing*:
assumes *rtrancp inference* $S S'$ **and** $\psi \in \text{fst } S$
shows $\psi \in \text{fst } S'$
using *assms* **by** (*induct rule: rtrancp-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 *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 *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 $N\ N' :: 'v\ clauses$

assumes *inference* $(N, already-used)\ (N', already-used')$

shows $total-over-m\ I\ N \implies total-over-m\ I\ N'$

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* $\psi\ \psi'$ **and** *finite* $(fst\ \psi)$

shows *finite* $(fst\ \psi')$

using *assms* **by** (*induct rule: inference.induct, auto simp add: simplify-preserves-finite*)

lemma *inference-clause-preserves-finite-snd*:

assumes *inference-clause* $\psi\ \psi'$ **and** *finite* $(snd\ \psi)$

shows *finite* $(snd\ \psi')$

using *assms* **by** (*induct rule: inference-clause.induct, auto*)

lemma *inference-preserves-finite-snd*:

assumes *inference* $\psi\ \psi'$ **and** *finite* $(snd\ \psi)$

shows *finite* $(snd\ \psi')$

using *assms inference-clause-preserves-finite-snd* **by** (*induct rule: inference.induct, fastforce*)

lemma *rtranclp-inference-preserves-finite*:

assumes *rtranclp inference* $\psi\ \psi'$ **and** *finite* $(fst\ \psi)$

shows *finite* $(fst\ \psi')$

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  $\psi$   $\psi'$ 
  and satisfiable  $\psi'$ 
  shows satisfiable  $\psi$ 
  using assms
proof induction
  case (tautology-deletion A P) note AP = this(1) and sat = this(2)
  let ?A' = A + {#Pos P#} + {#Neg P#}
  let ? $\psi'$  =  $\psi$  - {?A'}
  obtain I where
    I: I  $\models$  s ? $\psi'$  and
    cons: consistent-interp I and
    tot: 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 {I  $\models$  s  $\psi$  - {A + {#Pos P#} + {#Neg P#}}} 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 = this(1) and sat = this(2)
  have f3: simplify  $\psi$  ( $\psi$  - {A + {#L#} + {#L#}}  $\cup$  {A + {#L#}})
    using AL simplify.condensation by blast
  obtain LL :: 'a literal multiset set  $\Rightarrow$  'a literal set where
    f4: LL ( $\psi$  - {A + {#L#} + {#L#}}  $\cup$  {A + {#L#}})  $\models$  s  $\psi$  - {A + {#L#} + {#L#}}  $\cup$  {A
  + {#L#}}
     $\wedge$  consistent-interp (LL ( $\psi$  - {A + {#L#} + {#L#}}  $\cup$  {A + {#L#}}))
     $\wedge$  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: insert (A + {#L#} + {#L#}) ( $\psi$  - {A + {#L#} + {#L#}}) =  $\psi$ 
    using AL by fastforce
  have atms-of (A + {#L#} + {#L#}) = atms-of ({#L#} + A)
    by simp
  then show ?case
    using f5 f4 f3 by (metis (no-types) add commute satisfiable-def simplify-preserves-un-sat'
      total-over-m-insert total-over-m-union)
next
  case (subsumption A B) note A = this(1) and AB = this(2) and B = this(3) and sat = this(4)

```

```

let ? $\psi'$  =  $\psi - \{B\}$ 
obtain  $I$  where  $I: I \models_s ?\psi'$  and cons: consistent-interp  $I$  and tot: 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]:
  ( $\bigwedge xs:: 'v \text{ sem-tree. } (\bigwedge ys:: 'v \text{ sem-tree. } \text{sem-tree-size } ys < \text{sem-tree-size } xs \Longrightarrow P \ ys) \Longrightarrow P \ xs$ )
 $\Longrightarrow P \ xs$ 
  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  $ag \ (I \cup \{Pos \ v\}) \ \psi \wedge \text{partial-interps } ad \ (I \cup \{Neg \ v\}) \ \psi$ )

```

```

lemma simplify-preserve-partial-leaf:
  simplify  $N \ N' \Longrightarrow \text{partial-interps Leaf } I \ N \Longrightarrow \text{partial-interps Leaf } I \ N'$ 
  apply (induct rule: simplify.induct)
  using union-lcomm apply auto[1]
  apply (simp, metis atms-of-plus total-over-set-union true-clss-union)
  apply simp
  by (metis atms-of-ms-singleton mset-le-exists-conv subset-mset-def true-clss-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* ψ =
 (if *atms* = {} \vee \neg *finite atms*
 then *Leaf*
 else *Node (Min atms) (build-sem-tree (Set.remove (Min atms) atms) ψ)*
 (*build-sem-tree (Set.remove (Min atms) atms) ψ*)
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 ψ* **and** *finite ψ* **and** *consistent-interp I*
and *finite atms*
and *atms-of-ms ψ = atms \cup atms-of-s I* **and** *atms \cap atms-of-s I = {}*
shows *partial-interps (build-sem-tree atms ψ) I ψ*
using *assms*
proof (*induct arbitrary: I rule: build-sem-tree.induct*)
case (*1 atms ψ 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 ψ = atms-of-s Ia* **using** *un* **by** *auto*
then have *total-over-m Ia ψ* **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 ψ = 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:  $atms \neq \{\}$ 
  have build-sem-tree atms  $\psi = \text{Node } (Min \ atms) \ (\text{build-sem-tree } (Set.remove \ (Min \ atms) \ atms) \ \psi)$ 
    ( $\text{build-sem-tree } (Set.remove \ (Min \ atms) \ atms) \ \psi$ )
  using build-sem-tree.simps[of atms  $\psi$ ] f atms by metis

  have consistent-interp ( $Ia \cup \{Pos \ (Min \ atms)\}$ ) 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  $\psi = Set.remove \ (Min \ atms) \ atms \cup atms-of-s \ (Ia \cup \{Pos \ (Min \ atms)\})$ 
    using Min-in atms f un by fastforce
  moreover have  $disj'$ :  $Set.remove \ (Min \ atms) \ atms \cap atms-of-s \ (Ia \cup \{Pos \ (Min \ atms)\}) = \{\}$ 
    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 ( $\text{build-sem-tree } (Set.remove \ (Min \ atms) \ atms) \ \psi$ )
    ( $Ia \cup \{Pos \ (Min \ atms)\}$ )  $\psi$ 
    using IH1[of  $Ia \cup \{Pos \ (Min \ atms)\}$ ] atms f unsat finite by metis

  have consistent-interp ( $Ia \cup \{Neg \ (Min \ atms)\}$ ) 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  $\psi = Set.remove \ (Min \ atms) \ atms \cup atms-of-s \ (Ia \cup \{Neg \ (Min \ atms)\})$ 
    using  $\langle atms-of-ms \ \psi = Set.remove \ (Min \ atms) \ atms \cup atms-of-s \ (Ia \cup \{Pos \ (Min \ atms)\}) \rangle$  by
blast

  moreover have  $disj'$ :  $Set.remove \ (Min \ atms) \ atms \cap atms-of-s \ (Ia \cup \{Neg \ (Min \ atms)\}) = \{\}$ 
    using disj by auto
  moreover have finite ( $Set.remove \ (Min \ atms) \ atms$ ) using f by (simp add: remove-def)
  ultimately have subtree2: partial-interps ( $\text{build-sem-tree } (Set.remove \ (Min \ atms) \ atms) \ \psi$ )
    ( $Ia \cup \{Neg \ (Min \ atms)\}$ )  $\psi$ 
    using IH2[of  $Ia \cup \{Neg \ (Min \ atms)\}$ ] 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 ( $\text{build-sem-tree } (atms-of-ms \ \psi) \ \psi$ )  $\{\}$   $\psi$ 
proof -
  have consistent-interp  $\{\}$  unfolding consistent-interp-def by auto

```

moreover have $\text{atms-of-ms } \psi = \text{atms-of-ms } \psi \cup \text{atms-of-s } \{\}$ **unfolding** atms-of-s-def **by** *auto*
moreover have $\text{atms-of-ms } \psi \cap \text{atms-of-s } \{\} = \{\}$ **unfolding** atms-of-s-def **by** *auto*
moreover have $\text{finite } (\text{atms-of-ms } \psi)$ **unfolding** atms-of-ms-def **using** finite **by** *simp*
ultimately show $\text{partial-interps } (\text{build-sem-tree } (\text{atms-of-ms } \psi) \psi) \{\} \psi$
using $\text{partial-interps-build-sem-tree-atms-general}[\text{of } \psi \{\} \text{atms-of-ms } \psi]$ **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 $\text{count } \chi \ L = n$
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 $\text{inference}^{**} \psi \psi$

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* χ)

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* χ *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 ψ'' **and** χ''

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**

```

    tot:  $\forall I'. \text{total-over-m } I' \{?\chi'\} \longrightarrow \text{total-over-m } I' \{\chi''\}$ 
    using IH[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  $\psi :: 'v \text{ state}$  and  $\text{tree} :: 'v \text{ sem-tree}$ 
  assumes finite (fst  $\psi$ ) and already-used-inv  $\psi$ 
  and partial-interps tree I (fst  $\psi$ )
  shows  $\exists (\text{tree}' :: 'v \text{ sem-tree}) \ \psi'. \text{inference** } \psi \ \psi' \wedge \text{partial-interps tree}' I (\text{fst } \psi')$ 
     $\wedge (\text{sem-tree-size tree}' < \text{sem-tree-size tree} \vee \text{sem-tree-size tree} = 0)$ 
  using assms
proof (induct arbitrary: I rule: sem-tree-size)
  case (bigger xs I) note IH = 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 (cases xs, auto)
    {
      assume sem-tree-size ag = 0 and sem-tree-size ad = 0
      then have ag: ag = Leaf and ad: ad = Leaf by (cases ag, auto) (cases ad, auto)

      then obtain  $\chi \ \chi'$  where
         $\chi: \neg I \cup \{\text{Pos } v\} \models \chi$  and
        tot $\chi: \text{total-over-m } (I \cup \{\text{Pos } v\}) \{\chi\}$  and
         $\chi\psi: \chi \in \text{fst } \psi$  and
         $\chi': \neg I \cup \{\text{Neg } v\} \models \chi'$  and
        tot $\chi': \text{total-over-m } (I \cup \{\text{Neg } v\}) \{\chi'\}$  and
         $\chi'\psi: \chi' \in \text{fst } \psi$ 
      using part unfolding xs by auto
      have Posv:  $\neg \text{Pos } v \in\# \chi$  using  $\chi$  unfolding true-cls-def true-lit-def by auto
      have Negv:  $\neg \text{Neg } v \in\# \chi'$  using  $\chi'$  unfolding true-cls-def true-lit-def by auto
      {
        assume Neg $\chi: \neg \text{Neg } v \in\# \chi$ 
        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: rtrancp inference  $\psi \psi'$  and  $\chi^2 incl: \chi^2 \in fst \psi'$ 
      and  $\chi\chi^2 incl: \forall L. L : \# \chi \longleftrightarrow L : \# \chi^2$ 
      and count $\chi^2$ : count  $\chi^2$  (Neg  $v$ ) = 1
      and  $\varphi: \forall \varphi::'v$  literal multiset.  $\varphi \in fst \psi \longrightarrow \varphi \in fst \psi'$ 
      and  $I\chi: I \models \chi \longleftrightarrow I \models \chi^2$ 
      and tot-imp $\chi: \forall I'. total-over-m\ I' \{\chi\} \longrightarrow total-over-m\ I' \{\chi^2\}$ 
      using can-decrease-count[of  $\chi$  Neg  $v$  count  $\chi$  (Neg  $v$ )  $\psi$   $I$ ]  $\chi\psi \chi'\psi$  by auto

    have  $\chi' \in fst \psi'$  by (simp add:  $\chi'\psi \varphi$ )
    with pos
    obtain  $\psi'' \chi^{2'}$  where
      inf': inference**  $\psi' \psi''$ 
      and  $\chi^{2'} incl: \chi^{2'} \in fst \psi''$ 
      and  $\chi'\chi^{2'} incl: \forall L::'v$  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.  $\varphi \in fst \psi' \longrightarrow \varphi \in fst \psi''$ 
      and  $I\chi': I \models \chi' \longleftrightarrow I \models \chi^{2'}$ 
      and tot-imp $\chi': \forall I'. total-over-m\ I' \{\chi'\} \longrightarrow total-over-m\ I' \{\chi^{2'}\}$ 
      using can-decrease-count[of  $\chi' Pos\ v$  count  $\chi' (Pos\ v) \psi' I$ ] by auto

    obtain  $C$  where  $\chi^2: \chi^2 = C + \{\# Neg\ v\# \}$  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  $\chi\chi^2 incl$  count $\chi^2$ 
        count-diff count-single grOI insert-DiffM insert-DiffM2 multi-member-skip
        old.nat.distinct(2))

    obtain  $C'$  where
       $\chi^{2'}: \chi^{2'} = C' + \{\# Pos\ v\# \}$  and
      posC': Pos  $v \notin \# C'$  and
      negC': Neg  $v \notin \# C'$ 
    proof -
      assume a1:  $\bigwedge C'. \llbracket \chi^{2'} = C' + \{\# Pos\ v\# \}; Pos\ v \notin \# C'; Neg\ v \notin \# C' \rrbracket \Longrightarrow thesis$ 
      have f2:  $\bigwedge n. (n::nat) - n = 0$ 
        by simp
      have Neg  $v \notin \# \chi^{2'} - \{\# Pos\ v\# \}$ 
        using Negv  $\chi'\chi^{2'} incl$  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-imp $\chi'$  tot $\chi'$  total-over-m-sum tot-over-m-remove[of  $I$  Neg  $v$   $C'$ ] negC' posC'
  unfolding  $\chi^{2'}$  by (metis total-over-m-sum uminus-Neg)
have  $\neg I \models C + C'$ 
  using  $\chi$   $I\chi$   $\chi'$   $I\chi'$  unfolding  $\chi^2$   $\chi^{2'}$  true-cls-def Bex-mset-def
  by (metis add-gr-0 count-union true-cls-singleton true-cls-union-increase)
then have part-I- $\psi'''$ : partial-interps Leaf  $I$  (fst  $\psi'' \cup \{C + C'\}$ )
  using totC totC' by simp
  (metis  $\neg I \models C + C'$  atms-of-ms-singleton total-over-m-def total-over-m-sum)
{
  assume ( $\{\#Pos\ v\# \} + C', \{\#Neg\ v\# \} + C) \notin \text{snd } \psi''$ 
  then have inf'': inference  $\psi''$  (fst  $\psi'' \cup \{C + C'\}$ , snd  $\psi'' \cup \{(\chi^2, \chi^2)\}$ )
    using add commute  $\varphi'$   $\chi^2 \text{incl}$   $\langle \chi^2 \rangle \in \text{fst } \psi''$  unfolding  $\chi^2$   $\chi^{2'}$ 
    by (metis prod.collapse inference-step resolution)
  have inference**  $\psi$  (fst  $\psi'' \cup \{C + C'\}$ , snd  $\psi'' \cup \{(\chi^2, \chi^2)\}$ )
    using inf inf' inf'' rtrancplp-trans by auto
  moreover have sem-tree-size Leaf < sem-tree-size xs unfolding xs by auto
  ultimately have ?case using part-I- $\psi'''$  by (metis fst-conv)
}
moreover {
  assume a: ( $\{\#Pos\ v\# \} + C', \{\#Neg\ v\# \} + C) \in \text{snd } \psi''$ 
  then have ( $\exists \chi \in \text{fst } \psi''$ . ( $\forall I$ . total-over-m  $I \{C + C'\} \longrightarrow \text{total-over-m } I \{\chi\}$ )
     $\wedge (\forall I$ . total-over-m  $I \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models C' + C)$ )
     $\vee$  tautology ( $C' + C$ )
  proof -
    obtain p where p: Pos  $p \in \# (\{\#Pos\ v\# \} + C')$  and
    n: Neg  $p \in \# (\{\#Neg\ v\# \} + C)$  and
    decomp: ( $\exists \chi \in \text{fst } \psi''$ .
      ( $\forall I$ . total-over-m  $I \{(\{\#Pos\ v\# \} + C') - \{\#Pos\ p\# \}$ 
         $+ ((\{\#Neg\ v\# \} + C) - \{\#Neg\ p\# \})\}$ 
         $\longrightarrow \text{total-over-m } I \{\chi\}$ )
       $\wedge (\forall I$ . total-over-m  $I \{\chi\} \longrightarrow I \models \chi$ 
         $\longrightarrow I \models (\{\#Pos\ v\# \} + C') - \{\#Pos\ p\# \} + ((\{\#Neg\ v\# \} + C) - \{\#Neg\ p\# \})$ 
         $)$ 
       $\vee$  tautology ( $((\{\#Pos\ v\# \} + C') - \{\#Pos\ p\# \} + ((\{\#Neg\ v\# \} + C) - \{\#Neg\ p\# \})))$ )
    using a by (blast intro: allE[OF a-u-i- $\psi''$ [unfolding 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 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  $\exists \chi \in \text{fst } \psi''$ .  $(\forall I. \text{total-over-m } I \{C+C'\} \longrightarrow \text{total-over-m } I \{\chi\})$ 
     $\wedge (\forall I. \text{total-over-m } I \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models C' + C)$ 
    then obtain  $\vartheta$  where  $\vartheta: \vartheta \in \text{fst } \psi''$  and
     $\text{tot-}\vartheta\text{-CC'}: \forall I. \text{total-over-m } I \{C+C'\} \longrightarrow \text{total-over-m } I \{\vartheta\}$  and
     $\vartheta\text{-inv}: \forall I. \text{total-over-m } I \{\vartheta\} \longrightarrow I \models \vartheta \longrightarrow I \models C' + C$  by blast
    have partial-interps Leaf I (fst  $\psi''$ )
    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  $\neg \text{tautology } (C' + C)$ 
    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  $\psi$ )  $\longrightarrow$ 
  ( $\exists \text{tree}' \psi'. \text{inference}^{**} \psi \psi' \wedge \text{partial-interps tree}' (I \cup \{\text{Pos } v\}) (\text{fst } \psi')$ 
   $\wedge (\text{sem-tree-size tree}' < \text{sem-tree-size ag} \vee \text{sem-tree-size ag} = 0)))$ 
  using IH by auto
  ultimately obtain  $\psi' :: 'v \text{ state}$  and  $\text{tree}' :: 'v \text{ sem-tree}$  where
  inf:  $\text{inference}^{**} \psi \psi'$ 
  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 rtranclp.rtrancl-refl a-u-i by blast

have partial-interps ag (I  $\cup$  {Pos v}) (fst  $\psi'$ )
using rtranclp-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  $\psi :: 'v :: \text{linorder}$  state
assumes
  unsat:  $\neg$ satisfiable (fst  $\psi$ ) and
  finite: finite (fst  $\psi$ ) and
  a-u-v: already-used-inv  $\psi$ 
shows  $\exists \psi'. (\text{inference** } \psi \psi' \wedge \{\#\} \in \text{fst } \psi')$ 
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  $\chi\psi$ :  $\chi \in \text{fst } \psi$ 
    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 rtranclp-inference-preserves-finite inf H(4) by metis

```

```

    moreover have unsatisfiable (fst  $\psi'$ )
      using inference-preserves-unsat inf bigger.premis(2) by blast
    moreover have already-used-inv  $\psi'$ 
      using H(5) inf rtranclp-inference-preserves-already-used-inv[of  $\psi \psi'$ ] by auto
    ultimately have ?case using inf rtranclp-trans part' H(1) by fastforce
  }
  ultimately show ?case by (cases 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  $\exists \psi'. (\text{rtranclp inference } \psi \psi' \wedge \{\#\} \in \text{fst } \psi')$ 
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 rtranclp inference  $\psi \psi'$  and  $\{\#\} \in \text{fst } \psi'$ 
  shows unsatisfiable (fst  $\psi$ )
  using assms by (meson rtranclp-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  $L \in \# \chi \wedge \neg L \in \# \chi$  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:  $l\psi$ )
    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-clss-def apply auto
  using assms true-clss-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 ψ'

```

  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 ‹ $\chi \in \psi'$ › 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 tranclpD)

```

12.5 Resolution and Invariants

```

inductive resolution :: 'v state  $\Rightarrow$  'v state  $\Rightarrow$  bool where
  full1-simp: full1 simplify  $N \ N' \Longrightarrow$  resolution ( $N$ , already-used) ( $N'$ , already-used) |
  inferring: inference ( $N$ , already-used) ( $N'$ , already-used')  $\Longrightarrow$  simplified  $N$ 
     $\Longrightarrow$  full simplify  $N' \ N'' \Longrightarrow$  resolution ( $N$ , already-used) ( $N''$ , already-used')

```

12.5.1 Invariants

```

lemma resolution-finite:
  assumes resolution  $\psi \ \psi'$  and finite (fst  $\psi$ )
  shows finite (fst  $\psi'$ )
  using assms by (induct rule: resolution.induct)
    (auto simp add: full1-def full-def rtranclp-simplify-preserves-finite
      dest: tranclp-into-rtranclp inference-preserves-finite)

```

```

lemma rtranclp-resolution-finite:
  assumes resolution**  $\psi \ \psi'$  and finite (fst  $\psi$ )
  shows finite (fst  $\psi'$ )
  using assms by (induct rule: rtranclp-induct, auto simp add: resolution-finite)

```

```

lemma resolution-finite-snd:
  assumes resolution  $\psi \ \psi'$  and finite (snd  $\psi$ )
  shows finite (snd  $\psi'$ )
  using assms apply (induct rule: resolution.induct, auto simp add: inference-preserves-finite-snd)
  using inference-preserves-finite-snd snd-conv by metis

```

```

lemma rtranclp-resolution-finite-snd:
  assumes resolution**  $\psi \ \psi'$  and finite (snd  $\psi$ )
  shows finite (snd  $\psi'$ )
  using assms by (induct rule: rtranclp-induct, auto simp add: resolution-finite-snd)

```

```

lemma resolution-always-simplified:
  assumes resolution  $\psi \ \psi'$ 
  shows simplified (fst  $\psi'$ )
  using assms by (induct rule: resolution.induct)
    (auto simp add: full1-def full-def)

```

```

lemma tranclp-resolution-always-simplified:
  assumes tranclp resolution  $\psi \ \psi'$ 
  shows simplified (fst  $\psi'$ )
  using assms by (induct rule: tranclp.induct, auto simp add: resolution-always-simplified)

```

```

lemma resolution-atms-of:
  assumes resolution  $\psi \ \psi'$  and finite (fst  $\psi$ )

```

shows $\text{atms-of-ms } (\text{fst } \psi') \subseteq \text{atms-of-ms } (\text{fst } \psi)$
 using **assms apply** (induct rule: *resolution.induct*)
 apply (*simp add: rtranclp-simplify-atms-of-ms tranclp-into-rtranclp full1-def*)
 by (*metis (no-types, lifting) contra-subsetD fst-conv full-def*
inference-preserves-atms-of-ms rtranclp-simplify-atms-of-ms subsetI)

lemma *rtranclp-resolution-atms-of*:
 assumes *resolution*** $\psi \psi'$ and *finite* ($\text{fst } \psi$)
 shows $\text{atms-of-ms } (\text{fst } \psi') \subseteq \text{atms-of-ms } (\text{fst } \psi)$
 using **assms apply** (induct rule: *rtranclp-induct*)
 using *resolution-atms-of rtranclp-resolution-finite* by **blast+**

lemma *resolution-include*:
 assumes *res*: *resolution* $\psi \psi'$ and *finite*: *finite* ($\text{fst } \psi$)
 shows $\text{fst } \psi' \subseteq \text{simple-clss } (\text{atms-of-ms } (\text{fst } \psi))$
proof –
 have *finite'*: *finite* ($\text{fst } \psi'$) using *local.finite res resolution-finite* by **blast**
 have *simplified* ($\text{fst } \psi'$) using *res finite' resolution-always-simplified* by **blast**
 then have $\text{fst } \psi' \subseteq \text{simple-clss } (\text{atms-of-ms } (\text{fst } \psi'))$
 using *simplified-in-simple-clss finite' simplified-imp-distinct-mset-tauto*[*of* $\text{fst } \psi'$] by **auto**
 moreover have $\text{atms-of-ms } (\text{fst } \psi') \subseteq \text{atms-of-ms } (\text{fst } \psi)$
 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*
simple-clss-mono)
qed

lemma *rtranclp-resolution-include*:
 assumes *res*: *tranclp resolution* $\psi \psi'$ and *finite*: *finite* ($\text{fst } \psi$)
 shows $\text{fst } \psi' \subseteq \text{simple-clss } (\text{atms-of-ms } (\text{fst } \psi))$
 using **assms apply** (induct rule: *tranclp.induct*)
 apply (*simp add: resolution-include*)
 by (*meson simple-clss-mono order-class.le-trans resolution-include*
rtranclp-resolution-atms-of rtranclp-resolution-finite tranclp-into-rtranclp)

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* $\subseteq \text{vars}'$
 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* ($\text{fst } S$)
 and $\text{atms-of-ms } (\text{fst } S) \subseteq \text{vars}$
 shows *already-used-all-simple* (*snd* ($\text{fst } S \cup \{\text{fst } S'\}$, *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  $H = \text{this}$ 
show ?case apply clarify
proof –
  fix  $A\ B\ v$ 
  assume  $(A, B) \in \text{snd}(\text{fst}(N, \text{already-used}))$ 
     $\cup \{\text{fst}(C + D, \text{already-used} \cup \{(\{\#Pos\ P\# \} + C, \{\#Neg\ P\# \} + D)\})\},$ 
     $\text{snd}(C + D, \text{already-used} \cup \{(\{\#Pos\ P\# \} + C, \{\#Neg\ P\# \} + D)\})\}$ 
  then have  $(A, B) \in \text{already-used} \vee (A, B) = (\{\#Pos\ P\# \} + C, \{\#Neg\ P\# \} + D)$  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 simplified-in H(1,5) by auto
    moreover have  $\text{simplified}\{B\}$  using eq simplified-in H(2,5) by auto
    moreover have  $\text{atms-of}\ A \subseteq \text{atms-of-ms}\ N$ 
    using eq H(1) atms-of-atms-of-ms-mono[of A N] by auto
    moreover have  $\text{atms-of}\ B \subseteq \text{atms-of-ms}\ N$ 
    using eq H(2) 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
qed

```

lemma *inference-preserves-already-used-all-simple:*

```

assumes inference S S'
and already-used-all-simple (snd S) vars
and simplified (fst S)
and  $\text{atms-of-ms}(\text{fst}\ S) \subseteq \text{vars}$ 
shows already-used-all-simple (snd S') 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 (snd S) vars
and  $\text{atms-of-ms}(\text{fst}\ S) \subseteq \text{vars}$ 
shows already-used-all-simple (snd S') 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 (snd (N'', already-used')) vars

```


using *inference-preserves-already-used-all-simple*[of $(N, \text{already-used})$] by *simp*
qed

lemma *rtrancpl-already-used-all-simple-inv*:

assumes *resolution*** $S\ S'$
and *already-used-all-simple* (*snd* S) *vars*
and *atms-of-ms* (*fst* S) \subseteq *vars*
and *finite* (*fst* S)
shows *already-used-all-simple* (*snd* S') *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') \subseteq *atms-of-ms* (*fst* S)

by (*simp* add: *infstar* *local.finite* *rtrancpl-resolution-atms-of*)

then have *atms-of-ms* (*fst* S') \subseteq *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* $S \subset$ *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* $S \subset$ *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* $S \subset$ *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* $S \subset$ *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 *simple-clss vars* \times *simple-clss vars*

lemma *already-used-all-simple-in-already-used-top*:

assumes *already-used-all-simple s vars* **and** *finite vars*

shows $s \subseteq \text{already-used-top vars}$

proof

fix x

assume $x-s: x \in s$

obtain $A B$ **where** $x: x = (A, B)$ **by** (*cases x, auto*)

then have *simplified {A}* **and** *atms-of A* \subseteq *vars* **using** *assms(1) x-s* **by** *fastforce+*

then have $A: A \in \text{simple-clss vars}$

using *simple-clss-mono[of atms-of A vars]* x *assms(2)*

simplified-imp-distinct-mset-tauto[of {A}]

distinct-mset-not-tautology-implies-in-simple-clss **by** *fast*

moreover have *simplified {B}* **and** *atms-of B* \subseteq *vars* **using** *assms(1) x-s x* **by** *fast+*

then have $B: B \in \text{simple-clss vars}$

using *simplified-imp-distinct-mset-tauto[of {B}]*

distinct-mset-not-tautology-implies-in-simple-clss

simple-clss-mono[of atms-of B vars] x *assms(2)* **by** *fast*

ultimately show $x \in \text{simple-clss vars} \times \text{simple-clss vars}$

unfolding x **by** *auto*

qed

lemma *already-used-top-finite*:

assumes *finite vars*

shows *finite (already-used-top vars)*

using *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 simple-clss-mono* **by** *auto*

lemma *already-used-all-simple-finite*:

fixes $s :: ('a \text{ literal multiset} \times 'a \text{ literal multiset}) \text{ set}$ **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* $\psi \equiv \text{card} (\text{already-used-top vars} - \psi)$

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 $?top = \text{simple-clss } ?vars \times \text{simple-clss } ?vars$

have $1: \text{card-simple vars (snd } \psi) = \text{card } ?top - \text{card (snd } \psi)$

```

    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  $\psi'$ ) vars
    using already-used-all-simple-inv res a-u-s assms(7) by blast
  have f: finite (snd  $\psi'$ ) using already-used-all-simple-finite a-u-s' finite-v by auto
  have 2: card-simple vars (snd  $\psi'$ ) = card ?top - 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)  $\geq$  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 *trancpl-resolution-card-simple-decreasing:*

```

  assumes trancpl 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: trancpl-induct)
  case (base  $\psi'$ )
  then show ?case by (simp add: resolution-card-simple-decreasing)
next
  case (step  $\psi' \psi''$ ) note res = this(1) and res' = this(2) 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 rtrancpl-already-used-all-simple-inv[OF trancpl-into-rtrancpl[OF res] a-u-s atms f-fst] .
  have finite (fst  $\psi'$ )
    by (meson finite-fst res rtrancpl-resolution-finite trancpl-into-rtrancpl)
  moreover have finite (snd  $\psi'$ ) using already-used-all-simple-finite[OF a-u-s' f-v] .
  moreover have simplified (fst  $\psi'$ ) using res trancpl-resolution-always-simplified by blast
  moreover have atms-of-ms (fst  $\psi'$ )  $\subseteq$  vars
    by (meson atms f-fst order.trans res rtrancpl-resolution-atms-of trancpl-into-rtrancpl)
  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 *trancpl-resolution-card-simple-decreasing-2:*

```

  assumes trancpl 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 $?vars = (atms-of-ms \text{ (fst } \psi))$
 have *already-used-all-simple* ($snd \ \psi$) $?vars$ **unfolding** *empty-snd* **by** *auto*
 moreover have $atms-of-ms \text{ (fst } \psi) \subseteq ?vars$ **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)* *trancp-resolution-card-simple-decreasing*[*of* $\psi \ \psi$] **by** *presburger*
qed

12.5.2 well-foundness if the relation

lemma *wf-simplified-resolution*:

assumes $f\text{-vars}$: *finite vars*

shows $wf \{ (y:: 'v:: linorder \text{ state}, x). (atms-of-ms \text{ (fst } x) \subseteq vars \wedge simplified \text{ (fst } x) \wedge finite \text{ (snd } x) \wedge finite \text{ (fst } x) \wedge already-used-all-simple \text{ (snd } x) \text{ vars}) \wedge resolution \text{ } x \ y) \}$

proof –

{
 fix $a \ b :: 'v:: linorder \text{ state}$
 assume $(b, a) \in \{ (y, x). (atms-of-ms \text{ (fst } x) \subseteq vars \wedge simplified \text{ (fst } x) \wedge finite \text{ (snd } x) \wedge finite \text{ (fst } x) \wedge already-used-all-simple \text{ (snd } x) \text{ vars}) \wedge resolution \text{ } x \ y) \}$
 then have
 $atms-of-ms \text{ (fst } a) \subseteq vars$ **and**
 $simp$: $simplified \text{ (fst } a)$ **and**
 $finite \text{ (snd } a)$ **and**
 $finite \text{ (fst } a)$ **and**
 $a\text{-u-v}$: $already-used-all-simple \text{ (snd } a) \text{ vars}$ **and**
 res : $resolution \text{ } a \ b$ **by** *auto*
 have $finite \text{ (already-used-top vars)}$ **using** $f\text{-vars}$ *already-used-top-finite* **by** *blast*
 moreover have $already-used-top \text{ vars} \subseteq already-used-top \text{ vars}$ **by** *auto*
 moreover have $snd \ b \subseteq already-used-top \text{ vars}$
 using *already-used-all-simple-in-already-used-top*[*of* $snd \ b \text{ vars}$]
 $a\text{-u-v}$ *already-used-all-simple-inv*[*OF* res] ($finite \text{ (fst } a)$) ($atms-of-ms \text{ (fst } a) \subseteq vars$) $f\text{-vars}$
 by *presburger*
 moreover have $snd \ a \subset snd \ b$ **using** *resolution-simplified-already-used-subset*[*OF* $res \ simp$] .
 ultimately have $finite \text{ (already-used-top vars)} \wedge already-used-top \text{ vars} \subseteq already-used-top \text{ vars} \wedge snd \ b \subseteq already-used-top \text{ vars} \wedge snd \ a \subset snd \ b$ **by** *metis*
 }
 then show $?thesis$ **using** *wf-bounded-set*[*of* $\{ (y:: 'v:: linorder \text{ state}, x). (atms-of-ms \text{ (fst } x) \subseteq vars \wedge simplified \text{ (fst } x) \wedge finite \text{ (snd } x) \wedge finite \text{ (fst } x) \wedge already-used-all-simple \text{ (snd } x) \text{ vars}) \wedge resolution \text{ } x \ y) \}$ $\lambda\cdot. already-used-top \text{ vars} \text{ snd}$] **by** *auto*
qed

lemma *wf-simplified-resolution'*:

assumes $f\text{-vars}$: *finite vars*

shows $wf \{ (y:: 'v:: linorder \text{ state}, x). (atms-of-ms \text{ (fst } x) \subseteq vars \wedge \neg simplified \text{ (fst } x) \wedge finite \text{ (snd } x) \wedge finite \text{ (fst } x) \wedge already-used-all-simple \text{ (snd } x) \text{ vars}) \wedge resolution \text{ } x \ y) \}$

unfolding *wf-def*

apply ($simp \text{ add: resolution-always-simplified}$)

by (*metis* (*mono-tags*, *hide-lams*) *fst-conv resolution-always-simplified*)

lemma *wf-resolution*:

assumes $f\text{-vars}$: *finite vars*

shows $wf \{ (y:: 'v:: linorder \text{ state}, x). (atms-of-ms \text{ (fst } x) \subseteq vars \wedge simplified \text{ (fst } x) \wedge finite \text{ (snd } x) \wedge finite \text{ (fst } x) \wedge already-used-all-simple \text{ (snd } x) \text{ vars}) \wedge resolution \text{ } x \ y) \}$

$\cup \{(y, x). (atms-of-ms (fst x) \subseteq vars \wedge \neg simplified (fst x) \wedge finite (snd x) \wedge finite (fst x) \wedge already-used-all-simple (snd x) vars) \wedge resolution x y)\} (is\ wf\ (?R \cup ?S))$

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* *trancplp-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*** ψ ψ'
shows *satisfiable* $\psi' \longrightarrow$ *satisfiable* ψ
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 rtranclp-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 rtranclp-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 rtranclp-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 rtranclp-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 rtranclp-simplify-preserve-partial-tree[of  $N$   $N'$   $t$   $I$ ] tranclp-into-rtranclp
  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 rtranclp-simplify-preserve-partial-tree[of  $N$   $N'$   $t$   $I$ ] tranclp-into-rtranclp
  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 rtrancp-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 (rename-tac n, 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 |  $\varphi$  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 | 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
  (({\#-/. - : setof -\#}))
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  $\equiv$  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 ($\lambda\varphi. op + (msetsum \{\#count \varphi L \mid L \in \# \varphi. 2 \leq count \varphi L\#\}) 0 = sum-count-ge-2$
proof –
show *folding* ($\lambda\varphi. op + (msetsum (image-mset (count \varphi) \{\# L : \# \varphi. 2 \leq count \varphi L\#\}))$
by *standard auto*
then interpret *sum-count-ge-2*:
folding ($\lambda\varphi. op + (msetsum \{\#count \varphi L \mid L \in \# \varphi. 2 \leq count \varphi L\#\}) 0 .$
show *folding.F* ($\lambda\varphi. op + (msetsum (image-mset (count \varphi) \{\# L : \# \varphi. 2 \leq count \varphi L\#\})) 0$
 $= sum-count-ge-2$ **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 $nn :: nat \Rightarrow nat \Rightarrow nat$ **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 *simplify-finite-measure-decrease*:
simplify $N\ N' \implies finite\ N \implies card\ N' + \Xi N' < card\ N + \Xi N$
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.premis*)
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' ≤ 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  $\exists \{?C'\} < \exists \{?C\}$ 
proof -
  have mset-decomp:
     $\{\# La \in \# A. (L = La \longrightarrow \text{Suc } 0 \leq \text{count } A \text{ } La) \wedge (L \neq La \longrightarrow 2 \leq \text{count } A \text{ } La)\#\}$ 
    =  $\{\# La \in \# A. L \neq La \wedge 2 \leq \text{count } A \text{ } La\#\} +$ 
     $\{\# La \in \# A. L = La \wedge \text{Suc } 0 \leq \text{count } A \text{ } L\#\}$ 
    by (auto simp: multiset-eq-iff ac-simps)
  have mset-decomp2:  $\{\# La \in \# A. L \neq La \longrightarrow 2 \leq \text{count } A \text{ } La\#\} =$ 
     $\{\# La \in \# A. L \neq La \wedge 2 \leq \text{count } A \text{ } La\#\} + \text{replicate-mset } (\text{count } A \text{ } L) \text{ } L$ 
    by (auto simp: multiset-eq-iff)
  show ?thesis
    by (auto simp: mset-decomp mset-decomp2 filter-mset-eq ac-simps)
qed
have  $\exists ?N' < \exists N$ 
proof cases
  assume a1:  $?C' \in N$ 
  then show ?thesis
    proof -
      have f2:  $\bigwedge m M. \text{insert } (m::'a \text{ literal multiset}) (M - \{m\}) = M \cup \{\} \vee m \notin M$ 
        using Un-empty-right insert-Diff by blast
      have f3:  $\bigwedge m M Ma. \text{insert } (m::'a \text{ literal multiset}) M - \text{insert } m \text{ } Ma = M - \text{insert } m \text{ } Ma$ 
        by simp
      then have f4:  $\bigwedge M m. M - \{m::'a \text{ literal multiset}\} = M \cup \{\} \vee m \in M$ 
        using Diff-insert-absorb Un-empty-right by fastforce
      have f5:  $\text{insert } (A + \{\#L\# \} + \{\#L\# \}) N = N$ 
        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  $\exists (N - \{A + \{\#L\# \} + \{\#L\# \}\}) < \exists N$ 
        using f5 f4 by (metis Un-empty-right  $\exists \{A + \{\#L\# \}\} < \exists \{A + \{\#L\# \} + \{\#L\# \}\}$ 
          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
  qed
next
  assume  $?C' \notin N$ 
  have mset-decomp:
     $\{\# La \in \# A. (L = La \longrightarrow \text{Suc } 0 \leq \text{count } A \text{ } La) \wedge (L \neq La \longrightarrow 2 \leq \text{count } A \text{ } La)\#\}$ 
    =  $\{\# La \in \# A. L \neq La \wedge 2 \leq \text{count } A \text{ } La\#\} +$ 
     $\{\# La \in \# A. L = La \wedge \text{Suc } 0 \leq \text{count } A \text{ } L\#\}$ 
    by (auto simp: multiset-eq-iff ac-simps)
  have mset-decomp2:  $\{\# La \in \# A. L \neq La \longrightarrow 2 \leq \text{count } A \text{ } La\#\} =$ 
     $\{\# La \in \# A. L \neq La \wedge 2 \leq \text{count } A \text{ } La\#\} + \text{replicate-mset } (\text{count } A \text{ } L) \text{ } L$ 
    by (auto simp: multiset-eq-iff)

  show ?thesis
    using  $\exists \{A + \{\#L\# \}\} < \exists \{A + \{\#L\# \} + \{\#L\# \}\}$  condensation.hyps fin
    sum-count-ge-2.remove[of -  $A + \{\#L\# \} + \{\#L\# \}$ ]  $(?C' \notin N)$ 
    by (auto simp: mset-decomp mset-decomp2 filter-mset-eq)
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). finite N ∧ simplify N N'}
using assms apply (rule wfP-if-measure[of finite simplify λN. 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 = λN. ( $\exists N'. (N', N) \in r^* \wedge (\forall N''. (N'', N') \notin r)$ )
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 All ?P by blast
then show ?P N by blast
qed

```

lemma *rtranclp-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: wf {(N', N). simplify N N' ∧ 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 rtranclp-simplify-preserves-finite by blast

```

```

then have 2:  $\forall N''. \neg \text{simpify } N' N''$  using more by auto

show ?thesis using 1 2 by blast
qed

lemma finite-simplified-full1-simp:
  assumes finite N
  shows  $\text{simplified } N \vee (\exists N'. \text{full1 simpify } N N')$ 
  using rtranclp-simplify-terminates[OF assms] unfolding full1-def
  by (metis Nitpick.rtranclp-unfold)

lemma finite-simplified-full-simp:
  assumes finite N
  shows  $\exists N'. \text{full simpify } N N'$ 
  using rtranclp-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 = 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:  $\text{xs} = \text{Node } v \text{ ag ad}$  using sn0 by (cases xs, auto)
    {
      assume sem-tree-size ag = 0  $\wedge$  sem-tree-size ad = 0
      then have ag:  $\text{ag} = \text{Leaf}$  and ad:  $\text{ad} = \text{Leaf}$  by (cases ag, auto, cases ad, auto)

      then obtain  $\chi \chi'$  where
         $\chi: \neg I \cup \{\text{Pos } v\} \models \chi$  and
         $\text{tot}\chi: \text{total-over-m } (I \cup \{\text{Pos } v\}) \{\chi\}$  and
         $\chi\psi: \chi \in \text{fst } \psi$  and
         $\chi': \neg I \cup \{\text{Neg } v\} \models \chi'$  and
         $\text{tot}\chi': \text{total-over-m } (I \cup \{\text{Neg } v\}) \{\chi'\}$  and  $\chi'\psi: \chi' \in \text{fst } \psi$ 
        using part unfolding xs by auto
      have Posv:  $\text{Pos } v \notin \# \chi$  using  $\chi$  unfolding true-cls-def true-lit-def by auto
      have Negv:  $\text{Neg } v \notin \# \chi'$  using  $\chi'$  unfolding true-cls-def true-lit-def by auto
      {
        assume Neg $\chi: \neg \text{Neg } v \in \# \chi$ 
        then have  $\neg I \models \chi$  using  $\chi$  Posv unfolding true-cls-def true-lit-def by auto
        moreover have  $\text{total-over-m } I \{\chi\}$ 
          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 resolution**  $\psi$   $\psi$ 
  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 resolution**  $\psi$   $\psi$  using  $\chi'\psi$   $I\chi$  unfolding xs by auto
}
moreover {
  assume neg: Neg  $v \in \# \chi$  and pos: Pos  $v \in \# \chi'$ 
  have count  $\chi$  (Neg  $v$ ) = 1
    using simplified-count[OF simp  $\chi\psi$ ] neg by (metis One-nat-def Suc-le-mono Suc-pred eq-iff le0)
  have count  $\chi'$  (Pos  $v$ ) = 1
    using simplified-count[OF simp  $\chi'\psi$ ] 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:  $\bigwedge C. [\chi = C + \{\#Neg v\#; Neg v \notin \# C; Pos v \notin \# C] \implies thesis$ 
    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) count  $\chi$  (Neg  $v$ ) = 1 add.commute multi-member-split zero-less-one)
    then have Pos  $v \notin \# mm \chi$  (Neg  $v$ )
      using f2 by (metis (no-types) Posv count  $\chi$  (Neg  $v$ ) = 1 add.right-neutral add-left-cancel count-single count-union less-nat-zero-code)
    then show ?thesis
      using f3 a1 by (metis (no-types) count  $\chi$  (Neg  $v$ ) = 1 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 count  $\chi'$  (Pos  $v$ ) = 1 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'  $\hookrightarrow I \models C + C'$  by (metis Un-insert-right insertII
partial-interps.simps(1) total-over-m-sum)
{
  assume  $(\{\#Pos\ v\# \} + C', \{\#Neg\ v\# \} + C) \notin \text{snd } \psi$ 
  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) rtranclp.rtrancl-into-rtrancl rtranclp.rtrancl-refl)
}
moreover {
  assume a:  $(\{\#Pos\ v\# \} + C', \{\#Neg\ v\# \} + C) \in \text{snd } \psi$ 
  then have  $(\exists \chi \in \text{fst } \psi. (\forall I. \text{total-over-m } I \{C+C'\} \longrightarrow \text{total-over-m } I \{\chi\})$ 
     $\wedge (\forall I. \text{total-over-m } I \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models C' + C)) \vee \text{tautology } (C' + C)$ 
  proof -
    obtain  $p$  where  $p: Pos\ p \in \# (\{\#Pos\ v\# \} + C') \wedge Neg\ p \in \# (\{\#Neg\ v\# \} + C)$ 
       $\wedge ((\exists \chi \in \text{fst } \psi. (\forall I. \text{total-over-m } I \{(\{\#Pos\ v\# \} + C') - \{\#Pos\ p\# \} + ((\{\#Neg\ v\# \} + C) - \{\#Neg\ p\# \})) \longrightarrow \text{total-over-m } I \{\chi\}) \wedge (\forall I. \text{total-over-m } I \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models ((\{\#Pos\ v\# \} + C') - \{\#Pos\ p\# \} + ((\{\#Neg\ v\# \} + C) - \{\#Neg\ p\# \}))) \vee \text{tautology } ((\{\#Pos\ v\# \} + C') - \{\#Pos\ p\# \} + ((\{\#Neg\ v\# \} + C) - \{\#Neg\ p\# \})))$ 
    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  $\exists \chi \in \text{fst } \psi. (\forall I. \text{total-over-m } I \{C+C'\} \longrightarrow \text{total-over-m } I \{\chi\})$ 
     $\wedge (\forall I. \text{total-over-m } I \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models C' + C)$ 
  then obtain  $\vartheta$  where
     $\vartheta: \vartheta \in \text{fst } \psi$  and
     $\text{tot-}\vartheta\text{-}CC': \forall I. \text{total-over-m } I \{C+C'\} \longrightarrow \text{total-over-m } I \{\vartheta\}$  and
     $\vartheta\text{-inv}: \forall I. \text{total-over-m } I \{\vartheta\} \longrightarrow I \models \vartheta \longrightarrow I \models C' + C$  by blast
  have partial-interps Leaf I (fst  $\psi$ )
    using tot-}\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  $\neg \text{tautology } (C' + C)$ 
      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 ( $I \cup \{\text{Pos } v\}$ ) (fst  $\psi$ )
  and partad: partial-interps ad ( $I \cup \{\text{Neg } v\}$ ) (fst  $\psi$ )
    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 ( $I \cup \{\text{Pos } v\}$ ) (fst  $\psi$ )  $\implies$  simplified (fst  $\psi$ )
       $\implies \exists \text{ tree}' \ \psi'. \text{ resolution}^{**} \ \psi \ \psi' \wedge \text{partial-interps tree}' (I \cup \{\text{Pos } v\}) (\text{fst } \psi')$ 
         $\wedge (\text{sem-tree-size tree}' < \text{sem-tree-size ag} \vee \text{sem-tree-size ag} = 0)$ 
      using IH[of ag I  $\cup \{\text{Pos } v\}$ ] by auto
    ultimately obtain  $\psi' :: 'v \text{ state}$  and  $\text{tree}' :: 'v \text{ sem-tree}$  where
      inf: resolution**  $\psi \ \psi'$ 
      and part: partial-interps tree' ( $I \cup \{\text{Pos } v\}$ ) (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 simp by blast

  have partial-interps ad ( $I \cup \{\text{Neg } v\}$ ) (fst  $\psi'$ )
    using rtranclp-resolution-preserve-partial-tree inf partad by fast
  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 ( $I \cup \{\text{Pos } v\}$ ) (fst  $\psi$ ) and
      partial-interps ad ( $I \cup \{\text{Neg } v\}$ ) (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 ( $I \cup \{\text{Neg } v\}$ ) (fst  $\psi$ )  $\longrightarrow$  simplified (fst  $\psi$ )
       $\longrightarrow (\exists \text{ tree}' \ \psi'. \text{ resolution}^{**} \ \psi \ \psi' \wedge \text{partial-interps tree}' (I \cup \{\text{Neg } v\}) (\text{fst } \psi')$ 
         $\wedge (\text{sem-tree-size tree}' < \text{sem-tree-size ad} \vee \text{sem-tree-size ad} = 0)))$ 
    using IH by blast
  ultimately obtain  $\psi' :: 'v \text{ state}$  and  $\text{tree}' :: 'v \text{ sem-tree}$  where
    inf: resolution**  $\psi \ \psi'$ 
    and part: partial-interps tree' ( $I \cup \{\text{Neg } v\}$ ) (fst  $\psi'$ )
    and size: sem-tree-size tree' < sem-tree-size ad  $\vee$  sem-tree-size ad = 0
    using finite part rtranclp.rtrancl-refl a-u-i simp by blast

  have partial-interps ag ( $I \cup \{\text{Pos } v\}$ ) (fst  $\psi'$ )
    using rtranclp-resolution-preserve-partial-tree inf partag by fast

```

```

    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 resolution-completeness-inv:
  fixes  $\psi :: 'v :: \text{linorder state}$ 
  assumes
    unsat:  $\neg \text{satisfiable } (\text{fst } \psi)$  and
    finite: finite (fst  $\psi$ ) and
    a-u-v: already-used-inv  $\psi$ 
  shows  $\exists \psi'. (\text{resolution}^{**} \psi \psi' \wedge \{\#\} \in \text{fst } \psi')$ 
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  $\chi\psi$ :  $\chi \in \text{fst } \psi$ 
      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  $\neg \text{simplified } (\text{fst } \psi)$ 
          then have  $\exists \psi'. \text{full1 simplify } (\text{fst } \psi) \psi'$ 
            by (metis Nitpick.rtranclp-unfold bigger.premis(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  $\langle \text{full1 simplify } (\text{fst } \psi) N \rangle$  unfolding full1-def by blast
          ultimately have ?thesis using that by force
        }
      proof
        ultimately show ?thesis by auto
      end
    }
  end
end

```

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) rtracp-resolution-preserve-partial-tree apply blast
  using  $\psi_0$  bigger.prem(2) rtracp-resolution-preserves-unsat apply blast
  using  $\psi_0$  bigger.prem(3) rtracp-resolution-finite apply blast
  using rtracp-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 rtracp-resolution-finite by blast
have unsat: unsatisfiable (fst  $\psi'$ )
  using rtracp-resolution-preserves-unsat inf uns by metis
have a-u-i': already-used-inv  $\psi'$ 
  using a-u-v inf rtracp-resolution-already-used-inv[of  $\psi_0$   $\psi'$ ] by auto
have ?case
  using inf rtracp-trans[of resolution] H(1)[OF s part' unsat fin a-u-i']  $\psi_0$  by blast
}
ultimately show ?case by (cases 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 rtracp-resolution-preserves-already-used-inv:

```

assumes resolution** S S'
and already-used-inv S
shows already-used-inv S'
using assms
apply (induct rule: rtracp-induct)
  apply simp
using resolution-preserves-already-used-inv by fast

```

lemma resolution-completeness:

```

fixes  $\psi :: 'v :: \text{linorder}$  state
assumes unsat:  $\neg$ satisfiable (fst  $\psi$ )

```



```

and finite: 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 rtrancplp-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 rtrancplp-preserves-sat trancplp-into-rtrancplp unfolding full1-def apply fastforce
  by (metis fst-conv full-def inference-preserves-un-sat rtrancplp-preserves-sat
    satisfiable-carac' satisfiable-def)

lemma rtrancplp-resolution-preserves-sat:
  assumes resolution**  $S S'$ 
  and satisfiable (fst  $S$ )
  shows satisfiable (fst  $S'$ )
  using assms apply (induction rule: rtrancplp-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 rtrancplp-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:  $\text{snd } \psi = \{\}$ 
  shows  $(\exists \psi'. (\text{resolution}^{**} \psi \psi' \wedge \{\#\} \in \text{fst } \psi')) \longleftrightarrow \text{unsatisfiable (fst } \psi)$ 
  using assms resolution-completeness resolution-soundness by metis

lemma simplified-falsity:
  assumes simp: simplified  $\psi$ 
  and  $\{\#\} \in \psi$ 
  shows  $\psi = \{\{\#\}\}$ 
proof (rule ccontr)
  assume  $H: \neg ?thesis$ 
  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)  $\langle\{\#\} \subset \# \chi \rangle \langle\chi \in \psi\rangle$ ] 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 *rtranclp-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  $\chi s$ :  $\text{resolution}^{**} \psi (\chi s, a-u-v)$  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
      trancplp-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, 'lvl, 'mark) *marked-lit* =
is-marked: *Marked* (*lit-of*: 'v *literal*) (*level-of*: 'lvl) |
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 (*rename-tac a xs, case-tac a*) *auto*

lemma *is-marked-ex-Marked*:
 $\text{is-marked } L \implies \exists K \ lvl. L = \text{Marked } K \ lvl$
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 $Ls = \text{lit-of } ' (set \ Ls)$

lemma *lits-of-empty*[*simp*]:
 $\text{lits-of } [] = \{\}$ **unfolding** *lits-of-def* **by** *auto*

lemma *lits-of-cons*[*simp*]:
 $\text{lits-of } (L \ \# \ Ls) = \text{insert } (\text{lit-of } L) \ (\text{lits-of } Ls)$
unfolding *lits-of-def* **by** *auto*

lemma *lits-of-append*[*simp*]:
 $\text{lits-of } (l \ @ \ l') = \text{lits-of } l \cup \text{lits-of } l'$
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]:
 $set (map \text{lit-of } T) = \text{lits-of } T$
unfolding *lits-of-def* **by** *auto*

abbreviation *unmark* **where**
 $unmark\ M \equiv (\lambda a. \{\#\text{lit-of } a\}) \text{ ' } set\ M$

lemma *atms-of-ms-lambda-lit-of-is-atm-of-lit-of*[simp]:
 $atms-of-ms (unmark\ M') = atm-of \text{ ' } \text{lits-of } M'$
unfolding *atms-of-ms-def lits-of-def* **by** *auto*

lemma *lits-of-empty-is-empty*[iff]:
 $\text{lits-of } M = \{\} \longleftrightarrow M = []$
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]:
 $[] \models_{as} \psi \longleftrightarrow \psi = \{\}$
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]:
 $M \models_a A \Longrightarrow L \# M \models_a A$
unfolding *true-annot-def* **by** *auto*

lemma *true-annots-insert-l* [simp]:
 $M \models_{as} A \Longrightarrow L \# M \models_{as} A$
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*:

$L \# M \models_a A \implies \text{lit-of } L \not\in \# A \implies M \models_a A$

unfolding *true-annot-def* *true-cls-def* **by** *auto*

lemma *true-clss-singleton-lit-of-implies-incl*:

$I \models_s \text{unmark } MLs \implies \text{lits-of } MLs \subseteq I$

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-annots-def* *true-annot-def* *lits-of-def* *true-cls-def* *true-clss-cls-def*)

lemma *true-annots-marked-true-cls*[*iff*]:

$\text{map } (\lambda M. \text{Marked } M \ a) \ M \models_{as} N \longleftrightarrow \text{set } M \models_s N$

proof –

have *: $\text{lits-of } (\text{map } (\lambda M. \text{Marked } M \ a) \ M) = \text{set } M$ **unfolding** *lits-of-def* **by** *force*

show ?*thesis* **by** (*simp* *add*: *true-annots-true-cls* *)

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*:

$A \models_{as} \Psi \implies \text{unmark } A \models_{ps} \Psi$

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-cls-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]*:
 $set\ I \subseteq set\ I' \implies I \models_a N \implies I' \models_a N$
using *true-cls-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*:
 $set\ I \subseteq set\ I' \implies I \models_{as} N \implies I' \models_{as} N$
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
 $defined-lit\ I\ L \longleftrightarrow (\exists l. \text{Marked}\ L\ l \in set\ I) \vee (\exists P. \text{Propagated}\ L\ P \in set\ I)$
 $\vee (\exists l. \text{Marked}\ (-L)\ l \in set\ I) \vee (\exists P. \text{Propagated}\ (-L)\ P \in set\ I)$

abbreviation *undefined-lit* :: (*'a*, *'l*, *'m*) *marked-lit list* \Rightarrow *'a literal* \Rightarrow *bool*
where *undefined-lit* *I L* $\equiv \neg defined-lit\ I\ L$

lemma *defined-lit-rev[simp]*:
 $defined-lit\ (rev\ M)\ L \longleftrightarrow defined-lit\ M\ L$
unfolding *defined-lit-def* **by** *auto*

lemma *atm-imp-marked-or-proped*:
assumes $x \in set\ I$
shows
 $(\exists l. \text{Marked}\ (-\ lit-of\ x)\ l \in set\ I)$
 $\vee (\exists l. \text{Marked}\ (lit-of\ x)\ l \in set\ I)$
 $\vee (\exists l. \text{Propagated}\ (-\ lit-of\ x)\ l \in set\ I)$
 $\vee (\exists l. \text{Propagated}\ (lit-of\ x)\ l \in set\ I)$
using *assms marked-lit.exhaust-sel* **by** *metis*

lemma *literal-is-lit-of-marked*:
assumes $L = lit-of\ x$
shows $(\exists l. x = \text{Marked}\ L\ l) \vee (\exists l'. x = \text{Propagated}\ L\ l')$
using *assms* **by** (*cases x*) *auto*

lemma *true-annot-iff-marked-or-true-lit*:
 $defined-lit\ I\ L \longleftrightarrow ((lits-of\ I) \models_l L \vee (lits-of\ I) \models_l -L)$
unfolding *defined-lit-def* **by** (*auto simp add: lits-of-def rev-image-eqI*
dest!: literal-is-lit-of-marked)

lemma *consistent-interp* $(lits-of\ I) \implies I \models_{as} N \implies \text{satisfiable}\ N$
by (*simp add: true-annots-true-cls*)

lemma *defined-lit-map*:
 $defined-lit\ Ls\ L \longleftrightarrow atm-of\ L \in (\lambda l. atm-of\ (lit-of\ l))\ \text{' set}\ Ls$
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]*:
 $defined-lit\ I\ (-L) \longleftrightarrow defined-lit\ I\ L$

unfolding *defined-lit-def* **by** *auto*

lemma *Marked-Propagated-in-iff-in-lits-of*:

defined-lit I L \longleftrightarrow (*L* \in *lits-of I* \vee \neg *L* \in *lits-of I*)

unfolding *lits-of-def* *defined-lit-def*

by (*auto simp: rev-image-eqI*) (*rename-tac x, case-tac x, auto*)⁺

lemma *consistent-add-undefined-lit-consistent*[*simp*]:

assumes

consistent-interp (*lits-of Ls*) **and**

undefined-lit Ls L

shows *consistent-interp* (*insert L (lits-of Ls)*)

using *assms* **unfolding** *consistent-interp-def* **by** (*auto simp: Marked-Propagated-in-iff-in-lits-of*)

lemma *decided-empty*[*simp*]:

\neg *defined-lit* [] *L*

unfolding *defined-lit-def* **by** *simp*

13.2 Backtracking

fun *backtrack-split* :: ('v, 'l, 'm) *marked-lits*

\Rightarrow ('v, 'l, 'm) *marked-lits* \times ('v, 'l, 'm) *marked-lits* **where**

backtrack-split [] = ([], []) |

backtrack-split (*Propagated L P # mlits*) = *apfst* ((*op #*) (*Propagated L P*)) (*backtrack-split mlits*) |

backtrack-split (*Marked L l # mlits*) = ([], *Marked L l # mlits*)

lemma *backtrack-split-fst-not-marked*: $a \in \text{set } (\text{fst } (\text{backtrack-split } l)) \implies \neg \text{is-marked } a$

by (*induct l rule: marked-lit-list-induct*) *auto*

lemma *backtrack-split-snd-hd-marked*:

snd (*backtrack-split l*) \neq [] $\implies \text{is-marked } (\text{hd } (\text{snd } (\text{backtrack-split } l)))$

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''*, []) $\implies \forall l \in \text{set } M. \neg \text{is-marked } l$

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*:

$\exists l \in \text{set } M. \text{is-marked } l \implies \exists M' L' M''. \text{backtrack-split } M = (M'', L' \# M')$

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* $\square = [(\square, \square)]$ is necessary otherwise, we can call the *hd* function in the other pattern.

```
fun get-all-marked-decomposition :: ('a, 'l, 'm) marked-lits
   $\Rightarrow$  (('a, 'l, 'm) marked-lits  $\times$  ('a, 'l, 'm) marked-lits) list where
get-all-marked-decomposition (Marked L l # Ls) =
  (Marked L l # Ls,  $\square$ ) # 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  $\square$  = [(\square, \square)]
```

```
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 =  $\square \iff$  False
by (induct M, simp) (rename-tac a xs, case-tac a, auto)
```

```
lemma get-all-marked-decomposition-never-empty-sym[iff]:
   $\square =$  get-all-marked-decomposition M  $\iff$  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)  $\implies$  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')  $\iff$  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 = [(\square, A)]  $\implies$  snd (backtrack-split S) =  $\square$ 
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) #  $\square$ 
  shows a =  $\square \vee$  (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 (rename-tac L' l xs a b, 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)  $\in$  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)  $\in$  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.premis
by (cases get-all-marked-decomposition (M0 @ Marked K i # M1))
(auto dest!: get-all-marked-decomposition-decomp
arg-cong[of get-all-marked-decomposition - - hd])

```

qed
qed

lemma *get-all-marked-decomposition-snd-union:*

set $M = \bigcup (\text{set } \text{'snd' } \text{'set' } (\text{get-all-marked-decomposition } M)) \cup \{L \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$
(**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** $L = \text{this}$

hence $L \in ?Ls \ (L \# M)$ **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:*

$(a, b) \in \text{set } (\text{get-all-marked-decomposition } M') \implies$

$\exists b'. (a, b' @ b) \in \text{set } (\text{get-all-marked-decomposition } (M @ M'))$

apply (*induction* M *rule: marked-lit-list-induct*)

apply (*metis* *append-Nil*)

apply *auto*]

by (*rename-tac* $L' \ m \ xs$, *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 $tl \ (\text{get-all-marked-decomposition } (M' @ \text{Marked } L \ l \ \# \ M)) \neq []$

and $\forall l \in \text{set } M'. \neg \text{is-marked } l$

and $hd \ (tl \ (\text{get-all-marked-decomposition } (M' @ \text{Marked } L \ l \ \# \ M))) = (M0', M0)$

shows $hd \ (\text{get-all-marked-decomposition } (\text{Propagated } (-L) \ P \ \# \ M)) = (M0', \text{Propagated } (-L) \ P \ \# \ M0)$

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 $tl \ (\text{get-all-marked-decomposition } (\text{Propagated } (-L) \ P \ \# \ M))$

```

    = tl (tl (get-all-marked-decomposition (M' @ Marked L l # M)))
using assms by (induct M' rule: marked-lit-list-induct) auto

lemma get-all-marked-decomposition-hd-hd:
  assumes get-all-marked-decomposition Ls = (M, C) # (M0, M0') # l
  shows tl M = M0' @ M0 ∧ is-marked (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 = Marked L level
    have Ls = M0' @ M0
      using g a by (force intro: get-all-marked-decomposition-decomp)
    hence tl M = M0' @ M0 ∧ is-marked (hd M) using g a by auto
  }
  moreover {
    fix L P
    assume a: a = Propagated L P
    have tl M = M0' @ M0 ∧ is-marked (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) ∈ set (get-all-marked-decomposition M)
  shows ∃ c. M = c @ b @ a
  using assms apply (induct M rule: marked-lit-list-induct)
  apply simp
  by (rename-tac L' m xs, 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) ∈ set (get-all-marked-decomposition M)
  shows set b ⊆ set M and set a ⊆ set M
  using assms get-all-marked-decomposition-exists-prepend by fastforce+

lemma get-all-marked-decomposition-exists-prepend':
  assumes (a, b) ∈ set (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 (rename-tac L' m xs, 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) ∈ set (get-all-marked-decomposition M)
  shows set a ∪ set b ⊆ 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*
 $\longleftrightarrow (\forall (Ls, seen) \in \text{set } S. \text{unmark } Ls \cup N \models_{ps} \text{unmark } seen)$

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)]*
 $\longleftrightarrow \text{unmark } Ls \cup N \models_{ps} \text{unmark } seen$
unfolding *all-decomposition-implies-def* **by** *auto*

lemma *all-decomposition-implies-append*[iff]:
all-decomposition-implies *N (S @ S')*
 $\longleftrightarrow (\text{all-decomposition-implies } N S \wedge \text{all-decomposition-implies } N S')$
unfolding *all-decomposition-implies-def* **by** *auto*

lemma *all-decomposition-implies-cons-pair*[iff]:
all-decomposition-implies *N ((Ls, seen) \# S')*
 $\longleftrightarrow (\text{all-decomposition-implies } N [(Ls, seen)] \wedge \text{all-decomposition-implies } N S')$
unfolding *all-decomposition-implies-def* **by** *auto*

lemma *all-decomposition-implies-cons-single*[iff]:
all-decomposition-implies *N (l \# S')* \longleftrightarrow
 $(\text{unmark } (\text{fst } l) \cup N \models_{ps} \text{unmark } (\text{snd } l) \wedge$
 $\text{all-decomposition-implies } N S')$
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 $N \cup \{\{\# \text{lit-of } L \# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$
 $\models_{ps} (\lambda a. \{\# \text{lit-of } a \# \}) \text{ ' } \bigcup (\text{set ' snd ' set (get-all-marked-decomposition M))$

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 (*cases get-all-marked-decomposition M*) *auto*

moreover {

assume *a = []*

hence ?*case* **using** *Suc.prem*s *g* **by** *auto*

}

moreover {

assume *l: length a = 1* **and** *m: is-marked (hd a)* **and** *hd: hd a ∈ set M*

hence $(\lambda a. \{\# \text{lit-of } a \# \}) (\text{hd } a) \in \{\{\# \text{lit-of } L \# \} \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$ **by** *auto*

hence *H: unmark 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 ⊨_{ps} (λm. {\#lit-of m \#}) ' set b*

using *Suc.prem*s **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 (rename-tac a M, 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.premis 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) (rename-tac a xs, case-tac a, auto)

    have all-decomposition-implies N (get-all-marked-decomposition M')
      using Suc.premis unfolding Ls0 all-decomposition-implies-def by auto
    hence N: N ∪ { {#lit-of L#} | L. is-marked L ∧ L ∈ set M' }
      ≡ps (λa. {#lit-of a#}) ' ⋃ (set ' snd ' set (get-all-marked-decomposition M'))
      using IH length' by auto

    have l: N ∪ { {#lit-of L#} | L. is-marked L ∧ L ∈ set M' }
      ⊆ N ∪ { {#lit-of L#} | L. is-marked L ∧ L ∈ set M }
      using M'-in-M by auto
    hence ΨN: N ∪ { {#lit-of L#} | L. is-marked L ∧ L ∈ set M }
      ≡ps (λa. {#lit-of a#}) ' ⋃ (set ' snd ' set (get-all-marked-decomposition M'))
      using true-clss-clss-subset[OF l N] by auto
    have is-marked (hd Ls0) and LS: tl Ls0 = seen1 @ Ls1
      using get-all-marked-decomposition-hd-hd[of M] unfolding Ls0 Ls1 by auto

    have LSM: seen1 @ Ls1 = M' using get-all-marked-decomposition-decomp[of M] Ls1 by auto
    have M': set M' = Union (set ' snd ' set (get-all-marked-decomposition M'))
      ∪ { L | L. is-marked L ∧ L ∈ set M' }
      using get-all-marked-decomposition-snd-union by auto

    {
      assume Ls0 ≠ []
      hence hd Ls0 ∈ set M using get-all-marked-decomposition-fst-empty-or-hd-in-M Ls0 by blast
      hence N ∪ { {#lit-of L#} | L. is-marked L ∧ L ∈ set M } ≡p (λa. {#lit-of a#}) (hd Ls0)
        using ⟨is-marked (hd Ls0)⟩ by (metis (mono-tags, lifting) UnCI mem-Collect-eq
          true-clss-clss-in)
    } note hd-Ls0 = this

    have l: (λa. {#lit-of a#}) ' (⋃ (set ' snd ' set (get-all-marked-decomposition M'))
      ∪ { L | L. is-marked L ∧ L ∈ set M' })
      = (λa. {#lit-of a#}) '

```

```

     $\bigcup (\text{set } ' \text{snd } ' \text{set } (\text{get-all-marked-decomposition } M'))$ 
     $\cup \{ \{ \# \text{lit-of } L \# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M' \}$ 
  by auto
have  $N \cup \{ \{ \# \text{lit-of } L \# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M' \} \models_{ps}$ 
   $(\lambda a. \{ \# \text{lit-of } a \# \}) ' (\bigcup (\text{set } ' \text{snd } ' \text{set } (\text{get-all-marked-decomposition } M'))$ 
   $\cup \{ L \mid L. \text{ is-marked } L \wedge L \in \text{set } M' \})$ 
  unfolding l using N by (auto simp add: all-in-true-clss-clss)
hence  $N \cup \{ \{ \# \text{lit-of } L \# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M' \} \models_{ps} \text{unmark } (tl \text{ } Ls0)$ 
  using M' unfolding LS LSM by auto
hence  $t: N \cup \{ \{ \# \text{lit-of } L \# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M' \}$ 
   $\models_{ps} \text{unmark } (tl \text{ } Ls0)$ 
  by (blast intro: all-in-true-clss-clss)
hence  $N \cup \{ \{ \# \text{lit-of } L \# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M \}$ 
   $\models_{ps} \text{unmark } (tl \text{ } Ls0)$ 
  using M'-in-M true-clss-clss-subset[OF - t,
    of  $N \cup \{ \{ \# \text{lit-of } L \# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M \}$ ]
  by auto
hence  $N \cup \{ \{ \# \text{lit-of } L \# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M \} \models_{ps} \text{unmark } Ls0$ 
  using hd-Ls0 by (cases Ls0, auto)

moreover have  $\text{unmark } Ls0 \cup N \models_{ps} \text{unmark } \text{seen0}$ 
  using Suc.premis unfolding Ls0 all-decomposition-implies-def by simp
moreover have  $\bigwedge M \text{ Ma. } (M::'a \text{ literal multiset set}) \cup Ma \models_{ps} M$ 
  by (simp add: all-in-true-clss-clss)
ultimately have  $\Psi: N \cup \{ \{ \# \text{lit-of } L \# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M \} \models_{ps}$ 
   $\text{unmark } \text{seen0}$ 
  by (meson true-clss-clss-left-right true-clss-clss-union-and true-clss-clss-union-l-r)
have  $(\lambda a. \{ \# \text{lit-of } a \# \}) ' (\text{set } \text{seen0}$ 
   $\cup (\bigcup_{x \in \text{set}} (\text{get-all-marked-decomposition } M'). \text{set } (\text{snd } x)))$ 
   $= \text{unmark } \text{seen0}$ 
   $\cup (\lambda a. \{ \# \text{lit-of } a \# \}) ' (\bigcup_{x \in \text{set}} (\text{get-all-marked-decomposition } M'). \text{set } (\text{snd } x))$ 
  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 $N \cup \{ \{ \# \text{lit-of } L \# \} \mid L. \text{ is-marked } L \wedge L \in \text{set } M \} \models_{ps} \text{unmark } M$
 (is ?I \models_{ps} ?A)

proof –

```

have ?I  $\models_{ps} (\lambda a. \{ \# \text{lit-of } a \# \}) ' \{ L \mid L. \text{ is-marked } L \wedge L \in \text{set } M \}$ 
  by (auto intro: all-in-true-clss-clss)
moreover have ?I  $\models_{ps} (\lambda a. \{ \# \text{lit-of } a \# \}) ' \bigcup (\text{set } ' \text{snd } ' \text{set } (\text{get-all-marked-decomposition } M))$ 
  using all-decomposition-implies-trail-is-implied assms by blast
ultimately have  $N \cup \{ \{ \# \text{lit-of } m \# \} \mid m. \text{ is-marked } m \wedge m \in \text{set } M \}$ 
   $\models_{ps} (\lambda m. \{ \# \text{lit-of } m \# \}) ' \bigcup (\text{set } ' \text{snd } ' \text{set } (\text{get-all-marked-decomposition } M))$ 
   $\cup (\lambda m. \{ \# \text{lit-of } m \# \}) ' \{ m \mid m. \text{ is-marked } m \wedge m \in \text{set } M \}$ 
  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* $I \ \{ \varphi \}$ **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 (*rename-tac* $x \ L$, *case-tac* L) (*force intro: pos-lit-in-atms-of neg-lit-in-atms-of*) $+$

lemma *total-not-CNot*:

assumes *total-over-m* $I \ \{ \varphi \}$ **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*]:

$\text{atms-of-ms} \ (CNot \ C) = \text{atms-of } C$

unfolding *atms-of-ms-def atms-of-def CNot-def* **by** *fastforce*

lemma *true-clss-clss-contradiction-true-clss-clb-false:*

$C \in D \implies D \models_{ps} CNot\ C \implies D \models_p \{\#\}$

unfolding *true-clss-clss-def true-clss-clb-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* ' *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-clb-def*

proof (*intro allI impI*)

fix I

assume

tot: *total-over-m* $I\ (B \cup CNot\ \{\#L\#\})$ **and**

cons: *consistent-interp* I **and**

$I: I \models_s B$

have *total-over-m* $I\ (\{\{\#L\#\} \cup B)$ **using** *tot* **by** *auto*

hence $\neg I \models_s insert\ \{\#L\#\}\ B$

using *assms cons* **unfolding** *true-clss-clb-def* **by** *simp*

thus $I \models_s CNot\ \{\#L\#\}$

using *tot I* **by** (*cases L*) *auto*

qed

lemma *true-annots-true-clb-def-iff-negation-in-model:*

$M \models_{as} CNot\ C \iff (\forall L \in \# C. \neg L \in \text{lits-of } M)$

unfolding *CNot-def true-annots-true-clb true-clss-def* **by** *auto*

lemma *consistent-CNot-not-tautology:*

consistent-interp $M \implies M \models_s CNot\ D \implies \neg \text{tautology } D$

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-total-over-m[simp]:*

total-over-m $I\ (CNot\ C) = \text{total-over-set } I\ (\text{atms-of } C)$

unfolding *total-over-m-def total-over-set-def* **by** *auto*

lemma *uminus-lit-swap: $\neg(a::'a \text{ literal}) = i \iff a = -i$*

by *auto*

lemma *true-clss-clb-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-clb-def CNot-def total-over-m-def*

proof (*intro allI impI*)

fix I
assume tot : $total\text{-}over\text{-}set\ I\ (atms\text{-}of\text{-}ms\ (A \cup \{\{ \#L\# \}\}))$
and $cons$: $consistent\text{-}interp\ I$
and I : $I \models_s A$
let $?I = I \cup \{Pos\ P | P. P \in atms\text{-}of\ CC \wedge P \notin atm\text{-}of\ 'I\}$
have $cons'$: $consistent\text{-}interp\ ?I$
 using $cons$ **unfolding** $consistent\text{-}interp\text{-}def$
 by ($auto\ simp\ add$: $uminus\text{-}lit\text{-}swap\ atms\text{-}of\text{-}def\ rev\text{-}image\text{-}eqI$)
have I' : $?I \models_s A$
 using I $true\text{-}clss\text{-}union\text{-}increase$ **by** $blast$
have $tot\text{-}CNot$: $total\text{-}over\text{-}m\ ?I\ (A \cup CNot\ CC)$
 using $tot\ atms\text{-}of\text{-}s\text{-}def$ **by** ($fastforce\ simp\ add$: $total\text{-}over\text{-}m\text{-}def\ total\text{-}over\text{-}set\text{-}def$)

hence $tot\text{-}I\text{-}A\text{-}CC\text{-}L$: $total\text{-}over\text{-}m\ ?I\ (A \cup \{CC + \{ \#L\# \}\})$
 using tot **unfolding** $total\text{-}over\text{-}m\text{-}def\ total\text{-}over\text{-}set\text{-}atm\text{-}of$ **by** $auto$
hence $?I \models CC + \{ \#L\# \}$ **using** $CC\text{-}L\ cons'\ I'$ **unfolding** $true\text{-}clss\text{-}cls\text{-}def$ **by** $blast$
moreover
 have $?I \models_s CNot\ CC$ **using** $CNot\text{-}CC\ cons'\ I'$ $tot\text{-}CNot$ **unfolding** $true\text{-}clss\text{-}clss\text{-}def$ **by** $auto$
 hence $\neg A \models_p CC$
 by ($metis\ (no\text{-}types,\ lifting)\ I'\ atms\text{-}of\text{-}ms\text{-}CNot\text{-}atms\text{-}of\text{-}ms\ atms\text{-}of\text{-}ms\text{-}union\ cons'$
 $consistent\text{-}CNot\text{-}not\ tot\text{-}CNot\ total\text{-}over\text{-}m\text{-}def\ true\text{-}clss\text{-}cls\text{-}def$)
 hence $\neg ?I \models CC$ **using** $\langle ?I \models_s CNot\ CC \rangle\ cons'$ $consistent\text{-}CNot\text{-}not$ **by** $blast$
ultimately have $?I \models \{ \#L\# \}$ **by** $blast$
thus $I \models \{ \#L\# \}$
 by ($metis\ (no\text{-}types,\ lifting)\ atms\text{-}of\text{-}ms\text{-}union\ cons'\ consistent\text{-}CNot\text{-}not\ tot\ total\text{-}not\text{-}CNot$
 $total\text{-}over\text{-}m\text{-}def\ total\text{-}over\text{-}set\text{-}union\ true\text{-}clss\text{-}union\text{-}increase$)
qed

lemma $true\text{-}annots\text{-}CNot\text{-}lit\text{-}of\text{-}notin\text{-}skip$:
assumes LM : $L \# M \models_{as} CNot\ A$ **and** LA : $lit\text{-}of\ L \notin \# A \rightarrow lit\text{-}of\ L \notin \# A$
shows $M \models_{as} CNot\ A$
using LM **unfolding** $true\text{-}annots\text{-}def\ Ball\text{-}def$
proof ($intro\ allI\ impI$)
fix l
assume H : $\forall x. x \in CNot\ A \rightarrow L \# M \models_a x$ **and** l : $l \in CNot\ A$
hence $L \# M \models_a l$ **by** $auto$
thus $M \models_a l$ **using** $LA\ l$ **by** ($cases\ L$) ($auto\ simp\ add$: $CNot\text{-}def$)
qed

lemma $true\text{-}clss\text{-}clss\text{-}union\text{-}false\text{-}true\text{-}clss\text{-}clss\text{-}cnot$:
 $A \cup \{B\} \models_{ps} \{\{ \# \}\} \longleftrightarrow A \models_{ps} CNot\ B$
using $total\text{-}not\text{-}CNot\ consistent\text{-}CNot\text{-}not$ **unfolding** $total\text{-}over\text{-}m\text{-}def\ true\text{-}clss\text{-}clss\text{-}def$
by $fastforce$

lemma $true\text{-}annot\text{-}remove\text{-}hd\text{-}if\text{-}notin\text{-}vars$:
assumes $a \# M' \models_a D$
and $atm\text{-}of\ (lit\text{-}of\ a) \notin atms\text{-}of\ D$
shows $M' \models_a D$
using $assms\ true\text{-}cls\text{-}remove\text{-}hd\text{-}if\text{-}notin\text{-}vars$ **unfolding** $true\text{-}annot\text{-}def$ **by** $auto$

lemma $true\text{-}annot\text{-}remove\text{-}if\text{-}notin\text{-}vars$:
assumes $M @ M' \models_a D$
and $\forall x \in atms\text{-}of\ D. x \notin atm\text{-}of\ 'lits\text{-}of\ M$
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 $\forall x \in \text{atms-of-}ms\ D. x \notin \text{atm-of } \text{' } \textit{lits-of } M$
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 $\forall s \in \text{atms-of-}ms\ \{B\}. s \in \text{atm-of } \text{' } \textit{lits-of } A$
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** $\neg \textit{lits-of } A \models_l - L$

hence $\textit{atm-of } L \in \textit{atm-of } \text{' } \textit{lits-of } A$

using *assms(1)* **by** (*simp add: atm-of-lit-in-atms-of lits-of-def*)

hence $L \in \textit{lits-of } A \vee -L \in \textit{lits-of } A$

using *atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set* **by** *metis*

hence $L \in \textit{lits-of } A$ **using** $\langle \neg \textit{lits-of } A \models_l - L \rangle$ **by** *auto*

thus *False*

using LB *assms(2)* **unfolding** *true-annot-def true-lit-def true-cls-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 *no-dup* $L \equiv \textit{distinct } (\textit{map } (\lambda l. \textit{atm-of } (\textit{lit-of } l))\ L)$

lemma *no-dup-rev[simp]*:

$\textit{no-dup } (\textit{rev } M) \longleftrightarrow \textit{no-dup } M$

by (*auto simp: rev-map[symmetric]*)

lemma *no-dup-length-eq-card-atm-of-lits-of*:

assumes *no-dup* M

shows $\textit{length } M = \textit{card } (\textit{atm-of } \text{' } \textit{lits-of } M)$

using *assms* **unfolding** *lits-of-def* **by** (*induct M*) (*auto simp add: image-image*)

lemma *distinctconsistent-interp*:

$\textit{no-dup } M \implies \textit{consistent-interp } (\textit{lits-of } M)$

proof (*induct M*)

case *Nil*

show *?case* **by** *auto*

next

case (*Cons L M*)

hence *a1*: $\textit{consistent-interp } (\textit{lits-of } M)$ **by** *auto*

have *a2*: $\textit{atm-of } (\textit{lit-of } L) \notin (\lambda l. \textit{atm-of } (\textit{lit-of } l))\ \text{' } \textit{set } M$ **using** *Cons.prem*s **by** *auto*

have *undefined-lit* M (*lit-of L*)

using *a2 image-iff* **unfolding** *defined-lit-def* **by** *fastforce*

thus *?case*

using *a1* by *simp*
qed

lemma *distinct-get-all-marked-decomposition-no-dup*:
assumes $(a, b) \in \text{set } (\text{get-all-marked-decomposition } M)$
and *no-dup* *M*
shows *no-dup* $(a @ b)$
using *assms* by *force*

lemma *true-annots-lit-of-notin-skip*:
assumes $L \# M \models_{as} CNot\ A$
and $\neg \text{lit-of } L \notin \# A$
and *no-dup* $(L \# M)$
shows $M \models_{as} CNot\ A$

proof –
have $\forall l \in \# A. \neg l \in \text{lits-of } (L \# M)$
using *assms*(1) *in-CNot-implies-uminus*(2) by *blast*
moreover
have $\text{atm-of } (\text{lit-of } L) \notin \text{atm-of 'lits-of } M$
using *assms*(3) **unfolding** *lits-of-def* by *force*
hence $\neg \text{lit-of } L \notin \text{lits-of } M$ **unfolding** *lits-of-def*
by (*metis* (*no-types*) *atm-of-uminus imageI*)
ultimately have $\forall l \in \# A. \neg l \in \text{lits-of } M$
using *assms*(2) **unfolding** *Ball-mset-def* by (*metis insertE lits-of-cons uminus-of-uminus-id*)
thus *?thesis* by (*auto simp add: true-annots-def*)
qed

type-synonym *'v clauses* = *'v clause multiset*

abbreviation *true-annots-mset* (**infix** \models_{asm} 50) **where**
 $I \models_{asm} C \equiv I \models_{as} (\text{set-mset } C)$

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**
distinct-mset-mset $\Sigma \equiv \text{distinct-mset-set } (\text{set-mset } \Sigma)$

abbreviation *all-decomposition-implies-m* **where**
all-decomposition-implies-m $A\ B \equiv \text{all-decomposition-implies } (\text{set-mset } A)\ B$

abbreviation *atms-of-msu* **where**
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  $\models_{sext}$  set-mset C
end
theory CDCL-NOT
imports Partial-Annotated-Clausal-Logic List-More Wellfounded-More Partial-Clausal-Logic
begin

```

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```

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:
  no-dup M  $\implies$   $\neg$  lit-of xa = lit-of x  $\implies$  x  $\in$  set M  $\implies$  xa  $\notin$  set M
  by (metis atm-of-uminus distinct-map inj-on-eq-iff uminus-not-id')

```

```

lemma true-clss-single-iff-incl:
  I  $\models_s$  single ' B  $\longleftrightarrow$  B  $\subseteq$  I
  unfolding true-clss-def by auto

```

```

lemma atms-of-ms-single-atm-of[simp]:
  atms-of-ms { { #lit-of L# } | L. P L } = atm-of ' { lit-of L | L. P L }
  unfolding atms-of-ms-def by auto

```

```

lemma atms-of-uminus-lit-atm-of-lit-of:
  atms-of { #  $\neg$  lit-of x. x  $\in$  # A# } = atm-of ' (lit-of ' (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-of x# }) ' A) = atm-of ' (lit-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 list  $\Rightarrow$  nat where
 $\mu_C$  s b M  $\equiv$  ( $\sum i=0..<\text{length } M. M!i * b^{\wedge}(s+i - \text{length } M)$ )

```

```

lemma  $\mu_C$ -nil[simp]:
   $\mu_C$  s b [] = 0
  unfolding  $\mu_C$ -def by auto

```

```

lemma  $\mu_C$ -single[simp]:
   $\mu_C$  s b [L] = L * b  $^{\wedge}(s - \text{Suc } 0)$ 
  unfolding  $\mu_C$ -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:
  ( $\sum i=1..<\text{Suc } j. f i$ ) = ( $\sum i=0..<j. f (\text{Suc } i)$ )
  using set-sum-atLeastLessThan-add[of - 1 j] by force

```

lemma μ_C -cons:

$$\mu_C s b (L \# M) = L * b \wedge (s - 1 - \text{length } M) + \mu_C s b M$$

proof –

$$\text{have } \mu_C s b (L \# M) = (\sum_{i=0..<\text{length } (L\#M)}. (L\#M)!i * b \wedge (s + i - \text{length } (L\#M)))$$

unfolding μ_C -def **by** blast

$$\text{also have } \dots = (\sum_{i=0..<1}. (L\#M)!i * b \wedge (s + i - \text{length } (L\#M))) \\ + (\sum_{i=1..<\text{length } (L\#M)}. (L\#M)!i * b \wedge (s + i - \text{length } (L\#M)))$$

by (rule setsum-add-nat-ivl[symmetric]) simp-all

$$\text{finally have } \mu_C s b (L \# M) = L * b \wedge (s - 1 - \text{length } M) \\ + (\sum_{i=1..<\text{length } (L\#M)}. (L\#M)!i * b \wedge (s + i - \text{length } (L\#M)))$$

by auto

moreover {

$$\text{have } (\sum_{i=1..<\text{length } (L\#M)}. (L\#M)!i * b \wedge (s + i - \text{length } (L\#M))) = \\ (\sum_{i=0..<\text{length } (M)}. (L\#M)!(\text{Suc } i) * b \wedge (s + (\text{Suc } i) - \text{length } (L\#M)))$$

unfolding length-Cons set-sum-atLeastLessThan-Suc **by** blast

$$\text{also have } \dots = (\sum_{i=0..<\text{length } (M)}. M!i * b \wedge (s + i - \text{length } M))$$

by auto

$$\text{finally have } (\sum_{i=1..<\text{length } (L\#M)}. (L\#M)!i * b \wedge (s + i - \text{length } (L\#M))) = \mu_C s b M$$

unfolding μ_C -def .

ultimately show ?thesis **by** presburger

qed

lemma μ_C -append:

assumes $s \geq \text{length } (M @ M')$

shows $\mu_C s b (M @ M') = \mu_C (s - \text{length } M') b M + \mu_C s b M'$

proof –

$$\text{have } \mu_C s b (M @ M') = (\sum_{i=0..<\text{length } (M @ M')}. (M @ M')!i * b \wedge (s + i - \text{length } (M @ M')))$$

unfolding μ_C -def **by** blast

$$\text{moreover then have } \dots = (\sum_{i=0..<\text{length } M}. (M @ M')!i * b \wedge (s + i - \text{length } (M @ M'))) \\ + (\sum_{i=\text{length } M..<\text{length } (M @ M')}. (M @ M')!i * b \wedge (s + i - \text{length } (M @ M')))$$

by (auto intro!: setsum-add-nat-ivl[symmetric])

moreover

$$\text{have } \forall i \in \{0..<\text{length } M\}. (M @ M')!i * b \wedge (s + i - \text{length } (M @ M')) = M ! i * b \wedge (s - \text{length } M' \\ + i - \text{length } M)$$

using $\langle s \geq \text{length } (M @ M') \rangle$ **by** (auto simp add: nth-append ac-simps)

$$\text{then have } \mu_C (s - \text{length } M') b M = (\sum_{i=0..<\text{length } M}. (M @ M')!i * b \wedge (s + i - \text{length } (M @ M')))$$

unfolding μ_C -def **by** auto

$$\text{ultimately have } \mu_C s b (M @ M') = \mu_C (s - \text{length } M') b M$$

$$+ (\sum_{i=\text{length } M..<\text{length } (M @ M')}. (M @ M')!i * b \wedge (s + i - \text{length } (M @ M')))$$

by auto

moreover {

$$\text{have } (\sum_{i=\text{length } M..<\text{length } (M @ M')}. (M @ M')!i * b \wedge (s + i - \text{length } (M @ M'))) = \\ (\sum_{i=0..<\text{length } M'}. M'!i * b \wedge (s + i - \text{length } M'))$$

unfolding length-append set-sum-atLeastLessThan-add **by** auto

$$\text{then have } (\sum_{i=\text{length } M..<\text{length } (M @ M')}. (M @ M')!i * b \wedge (s + i - \text{length } (M @ M'))) = \mu_C s b M'$$

unfolding μ_C -def .

}

ultimately show ?thesis **by** presburger

qed

lemma μ_C -cons-non-empty-inf:

assumes $M\text{-ge-1}: \forall i \in \text{set } M. i \geq 1$ **and** $M: M \neq []$
shows $\mu_C \ s \ b \ M \geq b^{\wedge} (s - \text{length } M)$
using *assms* **by** (*cases* M) (*auto simp: mult-eq-if* $\mu_C\text{-cons}$)

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 $\mu_C\text{-bounded-non-degenerated}$:
fixes $b::nat$
assumes
 $b > 0$ **and**
 $M \neq []$ **and**
 $M\text{-le}: \forall i < \text{length } M. M!i < b$ **and**
 $s \geq \text{length } M$
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 $\forall i < \text{length } M. M!i = 0$ **using** $M\text{-le}$ **by** *auto*
then have $\mu_C \ s \ b \ M = 0$ **unfolding** $\mu_C\text{-def}$ **by** *auto*
then show *?thesis* **using** $\langle b > 0 \rangle$ **by** *auto*
next
case b
have $\forall i \in \{0..<\text{length } M\}. M!i * b^{\wedge} (s + i - \text{length } M) \leq (b-1) * b^{\wedge} (s + i - \text{length } M)$
using $M\text{-le}$ $\langle b > 1 \rangle$ **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 $\langle M \neq [] \rangle \langle b > 0 \rangle$ **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* $\text{Nat.add-diff-assoc2}$ 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 $\text{length } M$] $\langle b > 1 \rangle$
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 $\langle b > 1 \rangle$ **by** *auto*
also have $\dots = b^{\wedge} s$
by (*metis* *assms*(4) $\text{le-add-diff-inverse}$ power-add)

```

    finally show ?thesis unfolding  $\mu_C$ -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  $\mu_C$ -bounded:
  fixes  $b :: nat$ 
  assumes
     $M$ -le:  $\forall i < length\ M. M!i < b$  and
     $s \geq length\ M$ 
     $b > 0$ 
  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  $\langle b > 0 \rangle$  by auto
  next
    case  $M$ 
    show ?thesis using  $\mu_C$ -bounded-non-degenerated[ $OF\ M\ assms(1,2)$ ] by arith
  qed
qed

```

When $b = 0$, we cannot show that the measure is empty, since $0^0 = 1$.

```

lemma  $\mu_C$ -base-0:
  assumes  $length\ M \leq s$ 
  shows  $\mu_C\ s\ 0\ M \leq M!0$ 
proof -
  {
    assume  $s = length\ M$ 
    moreover {
      fix  $n$ 
      have  $(\sum i=0..<n. M!i * (0::nat) \wedge i) \leq M!0$ 
      apply (induction  $n$  rule: nat-induct)
      by simp (rename-tac  $n$ , case-tac  $n$ , auto)
    }
    ultimately have ?thesis unfolding  $\mu_C$ -def by auto
  }
  moreover
  {
    assume  $length\ M < s$ 
    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

```

$trail :: 'st \Rightarrow ('v, unit, unit) \text{ marked-lits and}$
 $clauses :: 'st \Rightarrow 'v \text{ clauses and}$
 $prepend-trail :: ('v, unit, unit) \text{ marked-lit} \Rightarrow 'st \Rightarrow 'st \text{ and}$
 $tl-trail :: 'st \Rightarrow 'st \text{ and}$
 $add-cls_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st \text{ and}$
 $remove-cls_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$
assumes
 $trail-prepend-trail[simp]:$
 $\bigwedge st L. \text{undefined-lit } (trail\ st) \text{ (lit-of } L) \implies trail\ (prepend-trail\ L\ st) = L \# trail\ st$
and
 $tl-trail[simp]: trail\ (tl-trail\ S) = tl\ (trail\ S) \text{ and}$
 $trail-add-cls_{NOT}[simp]: \bigwedge st C. \text{no-dup } (trail\ st) \implies trail\ (add-cls_{NOT}\ C\ st) = trail\ st \text{ and}$
 $trail-remove-cls_{NOT}[simp]: \bigwedge st C. trail\ (remove-cls_{NOT}\ C\ st) = trail\ st \text{ and}$

 $clauses-prepend-trail[simp]:$
 $\bigwedge st L. \text{undefined-lit } (trail\ st) \text{ (lit-of } L) \implies clauses\ (prepend-trail\ L\ st) = clauses\ st$
and
 $clauses-tl-trail[simp]: \bigwedge st. clauses\ (tl-trail\ st) = clauses\ st \text{ and}$
 $clauses-add-cls_{NOT}[simp]:$
 $\bigwedge st C. \text{no-dup } (trail\ st) \implies clauses\ (add-cls_{NOT}\ C\ st) = \{\#C\# \} + clauses\ st \text{ and}$
 $clauses-remove-cls_{NOT}[simp]: \bigwedge st C. clauses\ (remove-cls_{NOT}\ C\ st) = \text{remove-mset } C\ (clauses\ st)$
begin

function $reduce-trail-to_{NOT} :: 'a \text{ list} \Rightarrow 'st \Rightarrow 'st \text{ where}$
 $reduce-trail-to_{NOT}\ F\ S =$
 $(\text{if } length\ (trail\ S) = length\ F \vee trail\ S = [] \text{ then } S \text{ else } reduce-trail-to_{NOT}\ F\ (tl-trail\ S))$
by $fast+$
termination by $(relation\ measure\ (\lambda(-, S). length\ (trail\ S)))\ auto$
declare $reduce-trail-to_{NOT}.simps[simp\ del]$

lemma
shows
 $reduce-trail-to_{NOT}\text{-nil}[simp]: trail\ S = [] \implies reduce-trail-to_{NOT}\ F\ S = S \text{ and}$
 $reduce-trail-to_{NOT}\text{-eq-length}[simp]: length\ (trail\ S) = length\ F \implies reduce-trail-to_{NOT}\ F\ S = S$
by $(auto\ simp: reduce-trail-to_{NOT}.simps)$

lemma $reduce-trail-to_{NOT}\text{-length-ne}[simp]:$
 $length\ (trail\ S) \neq length\ F \implies trail\ S \neq [] \implies$
 $reduce-trail-to_{NOT}\ F\ S = reduce-trail-to_{NOT}\ F\ (tl-trail\ S)$
by $(auto\ simp: reduce-trail-to_{NOT}.simps)$

lemma $trail-reduce-trail-to_{NOT}\text{-length-le}:$
assumes $length\ F > length\ (trail\ S)$
shows $trail\ (reduce-trail-to_{NOT}\ F\ S) = []$
using $assms \text{ by } (induction\ F\ S \text{ rule: } reduce-trail-to_{NOT}.induct)$
 $(simp\ add: less-imp-diff-less\ reduce-trail-to_{NOT}.simps)$

lemma $trail-reduce-trail-to_{NOT}\text{-nil}[simp]:$
 $trail\ (reduce-trail-to_{NOT}\ []\ S) = []$
by $(induction\ []\ S \text{ rule: } reduce-trail-to_{NOT}.induct)$
 $(simp\ add: less-imp-diff-less\ reduce-trail-to_{NOT}.simps)$

lemma $clauses-reduce-trail-to_{NOT}\text{-nil}:$
 $clauses\ (reduce-trail-to_{NOT}\ []\ S) = clauses\ S$
by $(induction\ []\ S \text{ rule: } reduce-trail-to_{NOT}.induct)$

(simp add: less-imp-diff-less reduce-trail-to_{NOT}.simps)

lemma trail-reduce-trail-to_{NOT}-drop:
 trail (reduce-trail-to_{NOT} F S) =
 (if length (trail S) ≥ length F
 then drop (length (trail S) – length F) (trail S)
 else [])
apply (induction F S rule: reduce-trail-to_{NOT}.induct)
apply (rename-tac F S, case-tac trail S)
apply auto[]
apply (rename-tac list, case-tac Suc (length list) > length F)
prefer 2 **apply** simp
apply (subgoal-tac Suc (length list) – length F = Suc (length list – length F))
apply simp
apply simp
done

lemma reduce-trail-to_{NOT}-skip-beginning:
assumes trail S = F' @ F
shows trail (reduce-trail-to_{NOT} F S) = F
using assms **by** (auto simp: trail-reduce-trail-to_{NOT}-drop)

lemma reduce-trail-to_{NOT}-clauses[simp]:
 clauses (reduce-trail-to_{NOT} F S) = 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**
 trail-weight S ≡ map ((λl. 1 + length l) o snd) (get-all-marked-decomposition (trail S))

definition state-eq_{NOT} :: 'st ⇒ 'st ⇒ bool (**infix** ~ 50) **where**
 S ~ T ⟷ trail S = trail T ∧ clauses S = clauses T

lemma state-eq_{NOT}-ref[simp]:
 S ~ S
unfolding state-eq_{NOT}-def **by** auto

lemma state-eq_{NOT}-sym:
 S ~ T ⟷ T ~ S
unfolding state-eq_{NOT}-def **by** auto

lemma state-eq_{NOT}-trans:
 S ~ T ⟹ T ~ U ⟹ S ~ U
unfolding state-eq_{NOT}-def **by** auto

lemma
shows
 state-eq_{NOT}-trail: S ~ T ⟹ trail S = trail T **and**
 state-eq_{NOT}-clauses: S ~ T ⟹ clauses S = 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:

$trail\ S = trail\ T \implies trail\ (reduce_trail_to_{NOT}\ F\ S) = trail\ (reduce_trail_to_{NOT}\ F\ T)$
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 $reduce_trail_to_{NOT}\ F\ S \sim reduce_trail_to_{NOT}\ F\ T$

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 $trail_reduce_trail_to_{NOT}\ add_cls_{NOT}[simp]$:

$no_dup\ (trail\ S) \implies$

$trail\ (reduce_trail_to_{NOT}\ F\ (add_cls_{NOT}\ C\ S)) = trail\ (reduce_trail_to_{NOT}\ F\ S)$

by (rule $trail_eq_reduce_trail_to_{NOT}\ eq$) *simp*

lemma $reduce_trail_to_{NOT}\ trail_tl_trail_decomp[simp]$:

$trail\ S = F' @ Marked\ K\ () \# F \implies$

$trail\ (reduce_trail_to_{NOT}\ F\ (tl_trail\ S)) = F$

apply (rule $reduce_trail_to_{NOT}\ skip_beginning[of\ -\ tl\ (F' @ Marked\ K\ () \# [])]$)

by (cases F') (auto simp add: $tl_append\ reduce_trail_to_{NOT}\ skip_beginning$)

end

14.2.2 Definition of the operation

locale $propagate_ops =$

$dpll_state\ trail\ clauses\ prepend_trail\ tl_trail\ add_cls_{NOT}\ remove_cls_{NOT}$ **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**

$propagate_cond :: ('v, unit, unit)\ marked_lit \Rightarrow 'st \Rightarrow bool$

begin

inductive $propagate_{NOT} :: 'st \Rightarrow 'st \Rightarrow bool$ **where**

$propagate_{NOT}[intro]: C + \{\#L\# \} \in \# clauses\ S \implies trail\ S \models_{as}\ CNot\ C$

$\implies undefined_lit\ (trail\ S)\ L$

$\implies propagate_cond\ (Propagated\ L\ ())\ S$

$\implies T \sim prepend_trail\ (Propagated\ L\ ())\ S$

$\implies propagate_{NOT}\ S\ T$

inductive-cases $propagateE[elim]: propagate_{NOT}\ S\ T$

end

locale $decide_ops =$

$dpll_state\ trail\ clauses\ prepend_trail\ tl_trail\ add_cls_{NOT}\ remove_cls_{NOT}$ **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**

$add_cls_{NOT}\ remove_cls_{NOT} :: 'v\ clause \Rightarrow 'st \Rightarrow 'st$

```

begin
inductive decideNOT :: 'st ⇒ 'st ⇒ bool where
decideNOT[intro]: undefined-lit (trail S) L ⇒ atm-of L ∈ atms-of-msu (clauses S)
  ⇒ T ∼ prepend-trail (Marked L ()) S
  ⇒ decideNOT S T

inductive-cases decideE[elim]: decideNOT S S'
end

locale backjumping-ops =
  dpll-state trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
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 +
fixes
  backjump-conds :: 'v clause ⇒ 'v clause ⇒ 'v literal ⇒ 'st ⇒ 'st ⇒ bool
begin
inductive backjump where
trail S = F' @ Marked K () # F
  ⇒ T ∼ prepend-trail (Propagated L ()) (reduce-trail-toNOT F S)
  ⇒ C ∈ # clauses S
  ⇒ trail S ⊨as CNot C
  ⇒ undefined-lit F L
  ⇒ atm-of L ∈ atms-of-msu (clauses S) ∪ atm-of ' (lits-of (trail S))
  ⇒ clauses S ⊨pm C' + {#L#}
  ⇒ F ⊨as CNot C'
  ⇒ backjump-conds C C' L S T
  ⇒ 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-clNOT remove-clNOT +
  propagate-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT propagate-conds +
  decide-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT +
  backjumping-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT backjump-conds
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
  backjump-conds :: 'v clause ⇒ 'v clause ⇒ 'v literal ⇒ 'st ⇒ 'st ⇒ bool +
assumes
  bj-can-jump:
  ∧ S C F' K F L.
  inv S ⇒
  no-dup (trail S) ⇒
  trail S = F' @ Marked K () # F ⇒

```

$C \in \# \text{ clauses } S \implies$
 $\text{trail } S \models_{as} C \text{Not } C \implies$
 $\text{undefined-lit } F \text{ } L \implies$
 $\text{atm-of } L \in \text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of } ' (\text{lits-of } (F' @ \text{Marked } K () \# F)) \implies$
 $\text{clauses } S \models_{pm} C' + \{\#L\# \} \implies$
 $F \models_{as} C \text{Not } C' \implies$
 $\neg \text{no-step backjump } S$

begin

We cannot add a like condition $\text{atms-of } C' \subseteq \text{atms-of-ms } N$ because to ensure that we can backjump even if the last decision variable has disappeared.

The part of the condition $\text{atm-of } L \in \text{atm-of } ' (\text{lits-of } (F' @ \text{Marked } K () \# F))$ is important, otherwise you are not sure that you can backtrack.

14.3.1 Definition

We define dppl with backjumping:

inductive $\text{dppl-bj} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **for** $S :: 'st$ **where**

$\text{bj-decide}_{NOT} : \text{decide}_{NOT} S S' \implies \text{dppl-bj } S S' \mid$

$\text{bj-propagate}_{NOT} : \text{propagate}_{NOT} S S' \implies \text{dppl-bj } S S' \mid$

$\text{bj-backjump} : \text{backjump } S S' \implies \text{dppl-bj } S S'$

lemmas $\text{dppl-bj-induct} = \text{dppl-bj.induct}[\text{split-format}(\text{complete})]$

thm $\text{dppl-bj-induct}[\text{OF } \text{dppl-with-backjumping-ops-axioms}]$

lemma $\text{dppl-bj-all-induct}[\text{consumes } 2, \text{case-names } \text{decide}_{NOT} \text{ propagate}_{NOT} \text{ backjump}] :$

fixes $S \text{ } T :: 'st$

assumes

$\text{dppl-bj } S \text{ } T$ **and**

$\text{inv } S$

$\bigwedge L \text{ } T. \text{undefined-lit } (\text{trail } S) L \implies \text{atm-of } L \in \text{atms-of-msu } (\text{clauses } S)$

$\implies T \sim \text{prepend-trail } (\text{Marked } L ()) S$

$\implies P \text{ } S \text{ } T$ **and**

$\bigwedge C \text{ } L \text{ } T. C + \{\#L\# \} \in \# \text{ clauses } S \implies \text{trail } S \models_{as} C \text{Not } C \implies \text{undefined-lit } (\text{trail } S) L$

$\implies T \sim \text{prepend-trail } (\text{Propagated } L ()) S$

$\implies P \text{ } S \text{ } T$ **and**

$\bigwedge C \text{ } F' \text{ } K \text{ } F \text{ } L \text{ } C' \text{ } T. C \in \# \text{ clauses } S \implies F' @ \text{Marked } K () \# F \models_{as} C \text{Not } C$

$\implies \text{trail } S = F' @ \text{Marked } K () \# F$

$\implies \text{undefined-lit } F \text{ } L$

$\implies \text{atm-of } L \in \text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of } ' (\text{lits-of } (F' @ \text{Marked } K () \# F))$

$\implies \text{clauses } S \models_{pm} C' + \{\#L\# \}$

$\implies F \models_{as} C \text{Not } C'$

$\implies T \sim \text{prepend-trail } (\text{Propagated } L ()) (\text{reduce-trail-to}_{NOT} F S)$

$\implies P \text{ } S \text{ } T$

shows $P \text{ } S \text{ } T$

apply ($\text{induct } T \text{ rule: } \text{dppl-bj-induct}[\text{OF } \text{local.dppl-with-backjumping-ops-axioms}]$)

apply ($\text{rule } \text{assms}(1)$)

using $\text{assms}(3)$ **apply** blast

apply ($\text{elim } \text{propagateE}$) **using** $\text{assms}(4)$ **apply** blast

apply ($\text{elim } \text{backjumpE}$) **using** $\text{assms}(5)$ $\langle \text{inv } S \rangle$ **by** simp

14.3.2 Basic properties

First, some better suited induction principle **lemma** $\text{dppl-bj-clauses} :$

assumes $\text{dppl-bj } S \text{ } T$ **and** $\text{inv } S$

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} clauses S \longleftrightarrow I \models_{sm} 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
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: 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
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: 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
decomp: 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)*

proof *(induction rule: dpll-bj-all-induct)*

case *decide_{NOT}*

then show *?case using decomp by auto*

next

case *(propagate_{NOT} 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: unmark a ∪ set-mset ?N ⊨ps unmark (tl y)
  using decomp ay unfolding all-decomposition-implies-def by (simp add: M)+

moreover have unmark 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) ∪ unmark a
    ⊨ps unmark (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
qed

ultimately have unmark a ∪ set-mset ?N ⊨ps unmark ?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 unmark (fst (hd (get-all-marked-decomposition F)))
  ∪ set-mset (clauses S)
  ⊨ps unmark (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  $\subseteq$  atm-of ' lits-of F
    using  $\langle F \models_{as} CNot\ D \rangle$  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: unmark a  $\cup$  set-mset (clauses S)  $\models_{ps}$  unmark b
  using decomp unfolding all-decomposition-implies-def by (auto simp add: F)

  have F-D: unmark F  $\models_{ps}$  CNot D
  using  $\langle F \models_{as} CNot\ D \rangle$  by (simp add: true-annots-true-clss-clss)
  then have unmark a  $\cup$  unmark b  $\models_{ps}$  CNot D
  unfolding  $\langle F = b @ a \rangle$  by (simp add: image-Un sup commute)
  have a-N-CNot-D: unmark a  $\cup$  set-mset (clauses S)
     $\models_{ps}$  CNot D  $\cup$  unmark b
  apply (rule true-clss-clss-left-right)
  using a-N-b F-D unfolding  $\langle F = b @ a \rangle$  by (auto simp add: image-Un ac-simps)

  have a-N-D-L: unmark a  $\cup$  set-mset (clauses S)  $\models_p$  D+{#L#}
  by (simp add: N-C)
  have unmark a  $\cup$  set-mset (clauses S)  $\models_p$  {#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:
  length (get-all-marked-decomposition M) ≤ 1 + length M
by (induction M rule: marked-lit-list-induct) auto

```

```

lemma length-in-get-all-marked-decomposition-bounded:

```

```

  assumes i:i ∈ set (trail-weight S)
  shows i ≤ Suc (length (trail S))

```

```

proof –

```

```

  obtain a b where

```

```

    (a, b) ∈ set (get-all-marked-decomposition (trail S)) and

```

```

    ib: i = Suc (length b)

```

```

    using i by auto

```

```

  then obtain c where 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:

- $1 + \text{card}(\text{atms-of-ms } A)$: $\text{card}(\text{atms-of-ms } A)$ 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.
- $2 + \text{card}(\text{atms-of-ms } A)$: $\text{card}(\text{atms-of-ms } A)$ 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 literal multiset set  $\Rightarrow$  'a list  $\Rightarrow$  nat where

```

```

  unassigned-lit N M  $\equiv$  card (atms-of-ms N) – length M

```

```

lemma dpll-bj-trail-mes-increasing-prop:

```

```

  fixes M :: ('v, unit, unit) marked-lits and N :: 'v clauses

```

```

  assumes

```

```

    dpll-bj S T and

```

```

    inv S and

```

```

    NA: atms-of-msu (clauses S)  $\subseteq$  atms-of-ms A and

```

```

    MA: atm-of ' lits-of (trail S)  $\subseteq$  atms-of-ms A and

```

```

    n-d: no-dup (trail S) and

```

```

    finite: finite A

```

```

  shows  $\mu_C (1 + \text{card}(\text{atms-of-ms } A)) (2 + \text{card}(\text{atms-of-ms } A)) (\text{trail-weight } T)$ 

```

```

     $> \mu_C (1 + \text{card}(\text{atms-of-ms } A)) (2 + \text{card}(\text{atms-of-ms } A)) (\text{trail-weight } S)$ 

```

```

  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  $\subseteq$  atms-of-ms A

```

```

    using propagateNOT.hyps 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 (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 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  $\mu_C$ -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.hyps] 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 (cases 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  $\mu_C$ -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-le-A: length (Propagated L () # F) ≤ 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)
have tr-S-le-A: length (trail S) ≤ (card (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-le-A by simp
obtain rem where
  rem: map (λa. Suc (length (snd a))) (rev (get-all-marked-decomposition (F' @ Marked K () # F)))
  = map (λa. Suc (length (snd a))) (rev (get-all-marked-decomposition F)) @ rem
  using take-length-get-all-marked-decomposition-marked-sandwich[of F λa. Suc (length a) F' K]
  unfolding o-def by (metis append-take-drop-id)
then have rem: map (λa. Suc (length (snd a)))
  (get-all-marked-decomposition (F' @ Marked K () # F))
  = rev rem @ map (λa. Suc (length (snd a))) ((get-all-marked-decomposition F))
  by (simp add: rev-map[symmetric] rev-swap)
have length (rev rem @ map (λa. Suc (length (snd a))) (get-all-marked-decomposition F))
  ≤ Suc (card (atms-of-ms A))
  using arg-cong[OF rem, of length] tr-S-le-A
  length-get-all-marked-decomposition-length[of F' @ Marked K () # F] tr-S by auto
moreover
  { fix i :: nat and xs :: 'a list
    have i < length xs ⇒ length xs - Suc i < length xs
      by auto
    then have H: i < length xs ⇒ rev xs ! i ∈ 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 ∀ i < length rem. rev rem ! i < card (atms-of-ms A) + 2
  using tr-S-le-A length-in-get-all-marked-decomposition-bounded[of - S] unfolding tr-S
  by (force simp add: o-def rem dest!: H intro: length-get-all-marked-decomposition-length)
ultimately show ?case
  using μC-bounded[of rev rem card (atms-of-ms A)+2 unassigned-lit A l] T undef-L
  by (simp add: rem μC-append μC-cons F tr-S)
qed

```

lemma dpll-bj-trail-mes-decreasing-prop:

assumes dpll: dpll-bj S T **and** inv: inv S **and**
 N-A: atms-of-msu (clauses S) ⊆ atms-of-ms A **and**
 M-A: atm-of ' lits-of (trail S) ⊆ atms-of-ms A **and**
 nd: no-dup (trail S) **and**
 fin-A: finite A

shows (2+card (atms-of-ms A)) ^ (1+card (atms-of-ms A))
 - μ_C (1+card (atms-of-ms A)) (2+card (atms-of-ms A)) (trail-weight T)
 < (2+card (atms-of-ms A)) ^ (1+card (atms-of-ms A))
 - μ_C (1+card (atms-of-ms A)) (2+card (atms-of-ms A)) (trail-weight S)

proof -

```

let ?b = 2+card (atms-of-ms A)
let ?s = 1+card (atms-of-ms A)
let ?μ = μC ?s ?b
have M'-A: atm-of ' lits-of (trail T) ⊆ 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 ⇒ length xs - Suc i < length xs
    by auto
  then have H: i < length xs ⇒ xs ! i ∈ 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) ≤ 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) ≤ 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) ≤ 1 + card (atms-of-ms A)
  using l-M'-A length-get-all-marked-decomposition-length[of trail T] by auto
have bounded-M: ∀ i < length (trail-weight T). (trail-weight T)! i < card (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 dp11-bj-trail-mes-increasing-prop[OF dp11 inv N-A M-A nd fin-A]
have μC ?s ?b (trail-weight S) < μC ?s ?b (trail-weight T) by simp
moreover from μC-bounded[OF bounded-M l-trail-weight-M]
  have μC ?s ?b (trail-weight T) ≤ ?b ^ ?s by auto
ultimately show ?thesis by linarith
qed

lemma wf-dp11-bj:
  assumes fin: finite A
  shows wf {(T, S). dp11-bj S T
    ∧ atms-of-msu (clauses S) ⊆ atms-of-ms A ∧ atm-of ' lits-of (trail S) ⊆ atms-of-ms A
    ∧ no-dup (trail S) ∧ inv S}
  (is wf ?A)
proof (rule wf-bounded-measure[of -
  λ-. (2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A))
  λS. μC (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight S)])
fix a b :: 'st
let ?b = 2 + card (atms-of-ms A)
let ?s = 1 + card (atms-of-ms A)
let ?μ = μC ?s ?b
assume ab: (b, a) ∈ {(T, S). dp11-bj S T
  ∧ atms-of-msu (clauses S) ⊆ atms-of-ms A ∧ atm-of ' lits-of (trail S) ⊆ atms-of-ms A
  ∧ no-dup (trail S) ∧ inv S}
have fin-A: finite (atms-of-ms A)
  using fin by auto
have
  dp11-bj: dp11-bj a b and
  N-A: atms-of-msu (clauses a) ⊆ atms-of-ms A and
  M-A: atm-of ' lits-of (trail a) ⊆ 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) ⊆ atms-of-ms A
  by (meson M-A N-A ⟨dp11-bj a b⟩ dp11-bj-atms-in-trail-in-set inv)
have nd': no-dup (trail b)
  using ⟨dp11-bj a b⟩ dp11-bj-no-dup nd inv by blast
{ fix i :: nat and xs :: 'a list
  have i < length xs ⇒ length xs - Suc i < length xs
    by auto
  then have H: i < length xs ⇒ xs ! i ∈ 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) ≤ 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) ≤ 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) ≤ 1 + card (atms-of-ms A)
  using l-M'-A length-get-all-marked-decomposition-length[of trail b] by auto
have bounded-M: ∀ i < length (trail-weight b). (trail-weight b)! i < card (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 μC ?s ?b (trail-weight a) < μC ?s ?b (trail-weight b) by simp
moreover from μC-bounded[OF bounded-M l-trail-weight-M]
  have μC ?s ?b (trail-weight b) ≤ ?b ^ ?s by auto
ultimately show ?b ^ ?s ≤ ?b ^ ?s ∧
  μC ?s ?b (trail-weight b) ≤ ?b ^ ?s ∧
  μC ?s ?b (trail-weight a) < μC ?s ?b (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 $A :: 'v \text{ literal multiset set}$ **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  $\cup$  unmark ?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 (C  $\in$  set-mset (clauses S)) ( $\neg$  trail S  $\models_a$  C) 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#} | L. is-marked L ∧ L ∈ set ?M ∧ atm-of (lit-of L) ∉ atms-of-ms ?N }
have ∅[iff]: ∧ I. total-over-m I ( ?N ∪ ?O ∪ unmark ?M )
  ⟷ total-over-m I ( ?N ∪ unmark ?M )
  unfolding total-over-set-def total-over-m-def atms-of-ms-def by auto
assume ¬ ?thesis
then have [simp]: { {#lit-of L#} | L. is-marked L ∧ L ∈ set ?M }
  = { {#lit-of L#} | L. is-marked L ∧ L ∈ set ?M ∧ atm-of (lit-of L) ∉ atms-of-ms ?N }
  by auto
then have ?N ∪ ?O ⊨ps unmark ?M
  using all-decomposition-implies-propagated-lits-are-implied[OF decomp] by auto

then have ?I ⊨s unmark ?M
  using cons-I' I'-N tot-I' ⟨ ?I ⊨s ?N ∪ ?O ⟩ unfolding ∅ true-clss-clss-def by blast
then have lits-of ?M ⊆ ?I
  unfolding true-clss-def lits-of-def by auto
then have ?M ⊨as ?N
  using I'-N ⟨ C ∈ ?N ⟩ ⟨ ¬ ?M ⊨a C ⟩ cons-I' atms-N-M
  by (meson ⟨ trail S ⊨as CNot C ⟩ 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-K: ?M = F' @ Marked K () # F and
  nm: ∀ f ∈ set F'. ¬ 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 ∈ set ?M
  unfolding M-K by auto
let ?C = image-mset lit-of { #L ∈ #mset ?M. is-marked L ∧ L ≠ ?K# } :: 'v literal multiset
let ?C' = set-mset (image-mset (λL::'v literal. { #L# }) (?C + { #lit-of ?K# }))
have ?N ∪ { {#lit-of L#} | L. is-marked L ∧ L ∈ set ?M } ⊨ps unmark ?M
  using all-decomposition-implies-propagated-lits-are-implied[OF decomp] .
moreover have C': ?C' = { {#lit-of L#} | L. is-marked L ∧ L ∈ set ?M }
  unfolding M-K apply standard
  apply force
  using IntI by auto
ultimately have N-C-M: ?N ∪ ?C' ⊨ps unmark ?M
  by auto
have N-M-False: ?N ∪ (λL. { #lit-of L# }) ' (set ?M) ⊨ps { {#} }
  using M ⟨ ?M ⊨as CNot C ⟩ ⟨ C ∈ ?N ⟩ 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 ⟨ no-dup ?M ⟩ unfolding M-K by (simp add: defined-lit-map)
moreover
  have ?N ∪ ?C' ⊨ps { {#} }
  proof -
    have A: ?N ∪ ?C' ∪ unmark ?M =
      ?N ∪ unmark ?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 ⊨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  $\langle no\_dup (trail S) \rangle$  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

```

$add_cls_{NOT} \text{ remove_cls}_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st \text{ and}$
 $propagate_conds :: ('v, unit, unit) \text{ marked_lit} \Rightarrow 'st \Rightarrow bool \text{ and}$
 $inv :: 'st \Rightarrow bool \text{ and}$
 $backjump_conds :: 'v \text{ clause} \Rightarrow 'v \text{ clause} \Rightarrow 'v \text{ literal} \Rightarrow 'st \Rightarrow 'st \Rightarrow bool$
 $+$
assumes $dpll_bj_inv: \bigwedge S T. dpll_bj S T \Rightarrow inv S \Rightarrow inv T$
begin

lemma *rtrancpl-dpll-bj-inv*:
assumes $dpll_bj^{**} S T \text{ and } inv S$
shows $inv T$
using *assms* **by** (*induction rule: rtrancpl-induct*)
(auto simp add: dpll-bj-no-dup intro: dpll-bj-inv)

lemma *rtrancpl-dpll-bj-no-dup*:
assumes $dpll_bj^{**} S T \text{ and } inv S$
and *no-dup* (*trail S*)
shows *no-dup* (*trail T*)
using *assms* **by** (*induction rule: rtrancpl-induct*)
(auto simp add: dpll-bj-no-dup dest: rtrancpl-dpll-bj-inv dpll-bj-inv)

lemma *rtrancpl-dpll-bj-atms-of-ms-clauses-inv*:
assumes
 $dpll_bj^{**} S T \text{ and } inv S$
shows *atms-of-msu* (*clauses S*) = *atms-of-msu* (*clauses T*)
using *assms* **by** (*induction rule: rtrancpl-induct*)
(auto dest: rtrancpl-dpll-bj-inv dpll-bj-atms-of-ms-clauses-inv)

lemma *rtrancpl-dpll-bj-atms-in-trail*:
assumes
 $dpll_bj^{**} S T \text{ and}$
 $inv S \text{ and}$
 $atm_of \text{ ' (lits-of (trail S))} \subseteq atm_of_msu \text{ (clauses S)}$
shows $atm_of \text{ ' (lits-of (trail T))} \subseteq atm_of_msu \text{ (clauses T)}$
using *assms* **apply** (*induction rule: rtrancpl-induct*)
using *dpll-bj-atms-in-trail dpll-bj-atms-of-ms-clauses-inv rtrancpl-dpll-bj-inv* **by** *auto*

lemma *rtrancpl-dpll-bj-sat-iff*:
assumes $dpll_bj^{**} S T \text{ and } inv S$
shows $I \models_{sm} \text{clauses } S \longleftrightarrow I \models_{sm} \text{clauses } T$
using *assms* **by** (*induction rule: rtrancpl-induct*)
(auto dest!: dpll-bj-sat-iff simp: rtrancpl-dpll-bj-inv)

lemma *rtrancpl-dpll-bj-atms-in-trail-in-set*:
assumes
 $dpll_bj^{**} S T \text{ and}$
 $inv S$
 $atms_of_msu \text{ (clauses S)} \subseteq A \text{ and}$
 $atm_of \text{ ' (lits-of (trail S))} \subseteq A$
shows $atm_of \text{ ' (lits-of (trail T))} \subseteq A$
using *assms*
by (*induction rule: rtrancpl-induct*)
(auto dest: rtrancpl-dpll-bj-inv
simp add: dpll-bj-atms-in-trail-in-set rtrancpl-dpll-bj-atms-of-ms-clauses-inv
rtrancpl-dpll-bj-inv)

lemma *rtranclp-dpll-bj-all-decomposition-implies-inv*:

assumes

*dpll-bj** S T* **and**

inv S

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* **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*:

$\{(T, S). \text{dpll-bj}^{++} S T$

$\wedge \text{atms-of-msu (clauses } S) \subseteq \text{atms-of-ms } A \wedge \text{atm-of ' lits-of (trail } S) \subseteq \text{atms-of-ms } A$

$\wedge \text{no-dup (trail } S) \wedge \text{inv } S\}$

$\subseteq \{(T, S). \text{dpll-bj } S T \wedge \text{atms-of-msu (clauses } S) \subseteq \text{atms-of-ms } A$

$\wedge \text{atm-of ' lits-of (trail } S) \subseteq \text{atms-of-ms } A \wedge \text{no-dup (trail } S) \wedge \text{inv } S\}^+$

(**is** $?A \subseteq ?B^+$)

proof *standard*

fix *x*

assume *x-A*: $x \in ?A$

obtain *S T::'st* **where**

$x[\text{simp}]: x = (T, S)$ **by** (*cases x*) *auto*

have

*dpll-bj** S T* **and**

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**

inv S

using *x-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-A = this(4)* **and** *M-A = this(5)* **and** *nd = this(6)* **and** *inv = this(7)*

have $[\text{simp}]: \text{atms-of-msu (clauses } S) = \text{atms-of-msu (clauses } T)$

using *step rtranclp-dpll-bj-atms-of-ms-clauses-inv tranclp-into-rtranclp inv* **by** *fastforce*

have *no-dup (trail T)*

using *local.step nd rtranclp-dpll-bj-no-dup tranclp-into-rtranclp inv* **by** *fastforce*

moreover have *atm-of ' (lits-of (trail T)) \subseteq atms-of-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-A M-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* $\{(T, S). \text{dpll-bj}^{++} S T$

$\wedge \text{atms-of-msu (clauses } S) \subseteq \text{atms-of-ms } A \wedge \text{atm-of ' lits-of (trail } S) \subseteq \text{atms-of-ms } A$

$\wedge \text{no-dup } (\text{trail } S) \wedge \text{inv } S\}$
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*:

$\text{dpll-bj } S \ T \implies \text{inv } S \implies I \models_{\text{sextm}} \text{clauses } S \longleftrightarrow I \models_{\text{sextm}} \text{clauses } T$
by (*simp add: dpll-bj-clauses*)

lemma *rtranclp-dpll-bj-sat-ext-iff*:

$\text{dpll-bj}^{**} S \ T \implies \text{inv } S \implies I \models_{\text{sextm}} \text{clauses } S \longleftrightarrow I \models_{\text{sextm}} \text{clauses } T$
by (*induction rule: rtranclp-induct*) (*simp-all add: rtranclp-dpll-bj-inv dpll-bj-sat-ext-iff*)

theorem *full-dpll-backjump-final-state*:

fixes $A :: 'v \text{ literal multiset set}$ **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))

$\vee (\text{trail } T \models_{\text{asm}} \text{clauses } S \wedge \text{satisfiable } (\text{set-mset } (\text{clauses } S)))$

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))

$\vee (\text{trail } T \models_{\text{asm}} \text{clauses } T \wedge \text{satisfiable } (\text{set-mset } (\text{clauses } T)))$

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 $A :: 'v \text{ literal multiset set}$ **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) $\vee (\text{trail } T \models_{\text{asm}} N \wedge \text{satisfiable } (\text{set-mset } N))$

using *assms full-dpll-backjump-final-state*[*of* $S \ T \text{ set-mset } N$] **by** *auto*

lemma *trancpl-dpll-bj-trail-mes-decreasing-prop*:
assumes *dpll*: $dpll\text{-}bj^{++} S T$ **and** *inv*: $inv S$ **and**
N-A: $atms\text{-}of\text{-}msu (clauses S) \subseteq atms\text{-}of\text{-}ms A$ **and**
M-A: $atm\text{-}of \text{ ' } lits\text{-}of (trail S) \subseteq atms\text{-}of\text{-}ms A$ **and**
n-d: $no\text{-}dup (trail S)$ **and**
fin-A: $finite A$
shows $(2 + card (atms\text{-}of\text{-}ms A)) \wedge (1 + card (atms\text{-}of\text{-}ms A))$
 $\quad - \mu_C (1 + card (atms\text{-}of\text{-}ms A)) (2 + card (atms\text{-}of\text{-}ms A)) (trail\text{-}weight T)$
 $\quad < (2 + card (atms\text{-}of\text{-}ms A)) \wedge (1 + card (atms\text{-}of\text{-}ms A))$
 $\quad - \mu_C (1 + card (atms\text{-}of\text{-}ms A)) (2 + card (atms\text{-}of\text{-}ms A)) (trail\text{-}weight S)$
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 $atms\text{-}of\text{-}msu (clauses S) = atms\text{-}of\text{-}msu (clauses T)$
using *rtrancpl-dpll-bj-atms-of-ms-clauses-inv* **by** (*metis dpll-bj-clauses dpll-bj-inv inv st*
trancplD)
then have *N-A'*: $atms\text{-}of\text{-}msu (clauses T) \subseteq atms\text{-}of\text{-}ms A$
using *N-A* **by** *auto*
moreover have *M-A'*: $atm\text{-}of \text{ ' } lits\text{-}of (trail T) \subseteq atms\text{-}of\text{-}ms A$
by (*meson M-A N-A inv rtrancpl-dpll-bj-atms-in-trail-in-set st dpll*
trancpl.r-into-trancpl trancpl-into-rtrancpl trancpl-trans)
moreover have *nd*: $no\text{-}dup (trail T)$
by (*metis inv n-d rtrancpl-dpll-bj-no-dup st trancpl-into-rtrancpl*)
moreover have *inv T*
by (*meson dpll dpll-bj-inv inv rtrancpl-dpll-bj-inv st trancpl-into-rtrancpl*)
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-cls_{NOT} remove-cls_{NOT}
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* +
fixes
learn-cond :: *'v clause* \Rightarrow *'st* \Rightarrow *bool*
begin
inductive *learn* :: *'st* \Rightarrow *'st* \Rightarrow *bool* **where**
clauses S $\models_{pm} C \implies atms\text{-}of C \subseteq atms\text{-}of\text{-}msu (clauses S) \cup atm\text{-}of \text{ ' } (lits\text{-}of (trail S))$
 $\implies learn\text{-}cond C S$
 $\implies T \sim add\text{-}cls_{NOT} C S$
 $\implies learn S T$
inductive-cases *learnE*: *learn S T*

```

lemma learn- $\mu_C$ -stable:
  assumes learn  $S\ T$  and no-dup (trail  $S$ )
  shows  $\mu_C\ A\ B\ (\text{trail-weight } S) = \mu_C\ A\ B\ (\text{trail-weight } T)$ 
  using assms by (auto elim: learnE)
end

locale forget-ops =
  dpll-state trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
for
  trail :: ' $st \Rightarrow (v, \text{unit}, \text{unit})$  marked-lits' and
  clauses :: ' $st \Rightarrow v$  clauses' and
  prepend-trail :: ' $(v, \text{unit}, \text{unit})$  marked-lit  $\Rightarrow st \Rightarrow st$ ' and tl-trail :: ' $st \Rightarrow st$ ' and
  add-clNOT remove-clNOT :: ' $v$  clause  $\Rightarrow st \Rightarrow st +$ '
fixes
  forget-cond :: ' $v$  clause  $\Rightarrow st \Rightarrow \text{bool}$ '
begin
inductive forgetNOT :: ' $st \Rightarrow st \Rightarrow \text{bool}$ ' where
forgetNOT.clauses  $S - \text{replicate-mset } (\text{count } (\text{clauses } S)\ C)\ C \models_{pm} C$ 
 $\Rightarrow \text{forget-cond } C\ S$ 
 $\Rightarrow C \in \# \text{ clauses } S$ 
 $\Rightarrow T \sim \text{remove-cl}_{NOT} C\ S$ 
 $\Rightarrow \text{forget}_{NOT} S\ T$ 
inductive-cases forgetE: forgetNOT  $S\ T$ 

lemma forget- $\mu_C$ -stable:
  assumes forgetNOT  $S\ T$ 
  shows  $\mu_C\ A\ B\ (\text{trail-weight } S) = \mu_C\ A\ B\ (\text{trail-weight } T)$ 
  using assms by (auto elim!: forgetE)
end

locale learn-and-forgetNOT =
  learn-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT learn-cond +
forget-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT forget-cond
for
  trail :: ' $st \Rightarrow (v, \text{unit}, \text{unit})$  marked-lits' and
  clauses :: ' $st \Rightarrow v$  clauses' and
  prepend-trail :: ' $(v, \text{unit}, \text{unit})$  marked-lit  $\Rightarrow st \Rightarrow st$ ' and
  tl-trail :: ' $st \Rightarrow st$ ' and
  add-clNOT remove-clNOT :: ' $v$  clause  $\Rightarrow st \Rightarrow st$ ' and
  learn-cond forget-cond :: ' $v$  clause  $\Rightarrow st \Rightarrow \text{bool}$ '
begin
inductive learn-and-forgetNOT :: ' $st \Rightarrow st \Rightarrow \text{bool}$ '
where
lf-learn: learn  $S\ T \Rightarrow \text{learn-and-forget}_{NOT} S\ T$  |
lf-forget: forgetNOT  $S\ T \Rightarrow \text{learn-and-forget}_{NOT} S\ T$ 
end

```

14.4.2 Definition of CDCL

```

locale conflict-driven-clause-learning-ops =
  dpll-with-backjumping-ops trail clauses prepend-trail tl-trail add-clNOT remove-clNOT
  propagate-conds inv backjump-conds +
learn-and-forgetNOT trail clauses prepend-trail tl-trail add-clNOT remove-clNOT learn-cond
forget-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
backjump-conds :: 'v clause ⇒ 'v clause ⇒ 'v literal ⇒ 'st ⇒ 'st ⇒ bool and
learn-cond forget-cond :: 'v clause ⇒ 'st ⇒ bool
begin

inductive cdclNOT :: 'st ⇒ 'st ⇒ bool for S :: 'st where
c-dpll-bj: dpll-bj S S' ⇒ cdclNOT S S' |
c-learn: learn S S' ⇒ cdclNOT S S' |
c-forgetNOT: forgetNOT S S' ⇒ cdclNOT S S'

lemma cdclNOT-all-induct[consumes 1, case-names dpll-bj learn forgetNOT]:
fixes S T :: 'st
assumes cdclNOT S T and
dpll:  $\bigwedge T. \text{dpll-bj } S \ T \Rightarrow P \ S \ T$  and
learning:
 $\bigwedge C \ T. \text{clauses } S \models_{pm} C \Rightarrow$ 
 $\text{atms-of } C \subseteq \text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of } ' (\text{lits-of } (\text{trail } S)) \Rightarrow$ 
 $T \sim \text{add-cl}_{NOT} \ C \ S \Rightarrow$ 
 $P \ S \ T$  and
forgetting:  $\bigwedge C \ T. \text{clauses } S - \text{replicate-mset } (\text{count } (\text{clauses } S) \ C) \ C \models_{pm} C \Rightarrow$ 
 $C \in \# \text{clauses } S \Rightarrow$ 
 $T \sim \text{remove-cl}_{NOT} \ C \ S \Rightarrow$ 
 $P \ S \ T$ 
shows P S T
using assms(1) by (induction rule: cdclNOT.induct)
(auto intro: assms(2, 3, 4) elim!: learnE forgetE)+

lemma cdclNOT-no-dup:
assumes
cdclNOT S T and
inv S and
no-dup (trail S)
shows no-dup (trail T)
using assms by (induction rule: cdclNOT-all-induct) (auto intro: dpll-bj-no-dup)

```

Consistency of the trail lemma cdcl_{NOT}-consistent:

```

assumes
cdclNOT S T and
inv S and
no-dup (trail S)
shows consistent-interp (lits-of (trail T))
using cdclNOT-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 cdclNOT 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: cdclNOT-all-induct)
  (auto dest!: dpll-bj-atms-of-ms-clauses-inv set-mp simp add: atms-of-ms-def Union-eq)

lemma cdclNOT-atms-in-trail:
  assumes cdclNOT 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: cdclNOT-all-induct) (auto simp add: dpll-bj-atms-in-trail)

lemma cdclNOT-atms-in-trail-in-set:
  assumes
    cdclNOT 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: cdclNOT-all-induct)
    (simp-all add: dpll-bj-atms-in-trail-in-set dpll-bj-atms-of-ms-clauses-inv)

lemma cdclNOT-all-decomposition-implies:
  assumes cdclNOT 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: cdclNOT-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 (forgetNOT C T) note cls-C = this(1) and C = this(2) and T = this(3) and iniv = 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 unmark a  $\cup$  set-mset (clauses S)  $\models_{ps}$  unmark 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-clsNOT cls-C insert-Diff order-refl
        set-mset-minus-replicate-mset(1) state-eqNOT-clauses true-clss-clss-def
        true-clss-clss-insert)
    ultimately show unmark a  $\cup$  set-mset (clauses T)
       $\models_{ps}$  unmark b
      using true-clss-clss-generalise-true-clss-clss by blast
  qed
qed

```

Extension of models lemma *cdcl_{NOT}-bj-sat-ext-iff*:

assumes *cdcl_{NOT} S T* and *inv S* and *n-d: no-dup (trail S)*

shows $I \models_{\text{sextm}} \text{clauses } S \longleftrightarrow I \models_{\text{sextm}} \text{clauses } T$

using *assms*

proof (*induction rule:cdcl_{NOT}-all-induct*)

case *dpll-bj*

then show *?case* by (*simp add: dpll-bj-clauses*)

next

case (*learn C T*) note $T = \text{this}(3)$

{ fix *J*

assume

$I \models_{\text{sextm}} \text{clauses } S$ and

$I \subseteq J$ and

tot: total-over-m J (set-mset ({#C#} + (clauses S))) and

cons: consistent-interp J

then have $J \models_{\text{sm}} \text{clauses } S$ **unfolding** *true-clss-ext-def* by *auto*

moreover

with $\langle \text{clauses } S \models_{\text{pm}} C \rangle$ have $J \models C$

using *tot cons* **unfolding** *true-clss-cls-def* by *auto*

ultimately have $J \models_{\text{sm}} \{ \#C \# \} + \text{clauses } S$ by *auto*

}

then have $H: I \models_{\text{sextm}} (\text{clauses } S) \implies I \models_{\text{sext}} \text{insert } C (\text{set-mset } (\text{clauses } S))$

unfolding *true-clss-ext-def* by *auto*

show *?case*

apply *standard*

using *T n-d* **apply** (*auto simp add: H*)[]

using *T n-d* **apply** *simp*

by (*metis Diff-insert-absorb insert-subset subsetI subset-antisym*
true-clss-ext-decrease-right-remove-r)

next

case (*forget_{NOT} C T*) note $\text{cls-}C = \text{this}(1)$ and $T = \text{this}(3)$

{ fix *J*

assume

$I \models_{\text{sext}} \text{set-mset } (\text{clauses } S) - \{C\}$ and

$I \subseteq J$ and

tot: total-over-m J (set-mset (clauses S)) and

cons: consistent-interp J

then have $J \models_{\text{s}} \text{set-mset } (\text{clauses } S) - \{C\}$

unfolding *true-clss-ext-def* by (*meson Diff-subset total-over-m-subset*)

moreover

with $\text{cls-}C$ have $J \models C$

using *tot cons* **unfolding** *true-clss-cls-def*

by (*metis Un-commute forget_{NOT}.hyps(2) insert-Diff insert-is-Un mem-set-mset-iff order-refl*
set-mset-minus-replicate-mset(1))

ultimately have $J \models_{\text{sm}} (\text{clauses } S)$ 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  $cdcl_{NOT}\text{-inv}$ :  $\bigwedge S\ T. cdcl_{NOT}\ S\ T \implies inv\ S \implies inv\ T$ 
begin
sublocale dpll-with-backjumping
  apply unfold-locales
  using  $cdcl_{NOT}.simps\ cdcl_{NOT}\text{-inv}$  by auto

lemma rtracp-cdclNOT-inv:
   $cdcl_{NOT}^{**}\ S\ T \implies inv\ S \implies inv\ T$ 
  by (induction rule: rtracp-induct) (auto simp add:  $cdcl_{NOT}\text{-inv}$ )

lemma rtracp-cdclNOT-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: rtracp-induct) (auto intro:  $cdcl_{NOT}\text{-no-dup}\ rtracp\text{-}cdcl_{NOT}\text{-inv}$ )

lemma rtracp-cdclNOT-trail-clauses-bound:
  assumes
     $cdcl$ :  $cdcl_{NOT}^{**}\ S\ T$  and
     $inv$ :  $inv\ S$  and
     $n\text{-d}$ : no-dup (trail  $S$ ) and
     $atms\text{-clauses}\text{-}S$ :  $atms\text{-of}\text{-msu}\ (clauses\ S) \subseteq A$  and
     $atms\text{-trail}\text{-}S$ :  $atm\text{-of}\ ('(lits\text{-of}\ (trail\ S))) \subseteq A$ 
  shows  $atm\text{-of}\ ('(lits\text{-of}\ (trail\ T))) \subseteq A \wedge atms\text{-of}\text{-msu}\ (clauses\ T) \subseteq A$ 
  using  $cdcl$ 
proof (induction rule: rtracp-induct)
  case base
  then show ?case using  $atms\text{-clauses}\text{-}S\ atms\text{-trail}\text{-}S$  by simp
next
  case (step  $T\ U$ ) note  $st = this(1)$  and  $cdcl_{NOT} = this(2)$  and  $IH = this(3)$ 
  have  $inv\ T$  using  $inv\ st\ rtracp\text{-}cdcl_{NOT}\text{-inv}$  by blast
  have no-dup (trail  $T$ )
    using  $rtracp\text{-}cdcl_{NOT}\text{-no-dup}[of\ S\ T]\ st\ cdcl_{NOT}\ inv\ n\text{-d}$  by blast
  then have  $atms\text{-of}\text{-msu}\ (clauses\ U) \subseteq A$ 
    using  $cdcl_{NOT}\text{-}atms\text{-of}\text{-ms-clauses-decreasing}[OF\ cdcl_{NOT}]\ IH\ n\text{-d}\ \langle inv\ T \rangle$  by auto
  moreover
    have  $atm\text{-of}\ ('(lits\text{-of}\ (trail\ U))) \subseteq A$ 
      using  $cdcl_{NOT}\text{-}atms\text{-in}\text{-trail}\text{-in}\text{-set}[OF\ cdcl_{NOT},\ of\ A]\ \langle no\text{-dup}\ (trail\ T) \rangle$ 
      by (meson  $atms\text{-trail}\text{-}S\ atms\text{-clauses}\text{-}S\ IH\ \langle inv\ T \rangle\ cdcl_{NOT}$ )
    ultimately show ?case by fast
qed

lemma rtracp-cdclNOT-all-decomposition-implies:
  assumes  $cdcl_{NOT}^{**}\ S\ T$  and  $inv\ S$  and no-dup (trail  $S$ ) and
    all-decomposition-implies- $m\ (clauses\ S)\ (get\text{-all}\text{-marked}\text{-decomposition}\ (trail\ S))$ 
  shows
    all-decomposition-implies- $m\ (clauses\ T)\ (get\text{-all}\text{-marked}\text{-decomposition}\ (trail\ T))$ 
  using assms by (induction)
  (auto intro:  $rtracp\text{-}cdcl_{NOT}\text{-inv}\ cdcl_{NOT}\text{-all-decomposition-implies}\ rtracp\text{-}cdcl_{NOT}\text{-no-dup}$ )

lemma rtracp-cdclNOT-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: *rtrancpl-induct*)
using *cdcl_{NOT}-bj-sat-ext-iff* **by** (auto intro: *rtrancpl-cdcl_{NOT}-inv* *rtrancpl-cdcl_{NOT}-no-dup*)

definition *cdcl_{NOT}-NOT-all-inv* **where**

cdcl_{NOT}-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: *rtrancpl-cdcl_{NOT}-inv* *rtrancpl-cdcl_{NOT}-no-dup* *rtrancpl-cdcl_{NOT}-trail-clauses-bound*)

abbreviation *learn-or-forget* **where**

learn-or-forget $S \ T \equiv (\lambda S \ T. \text{learn } S \ T \vee \text{forget}_{\text{NOT}} S \ T) \ S \ T$

lemma *rtrancpl-learn-or-forget-cdcl_{NOT}*:

*learn-or-forget*** $S \ T \implies \text{cdcl}_{\text{NOT}}^{**} S \ T$

using *rtrancpl-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 $?_{\text{case}}$ **by** *simp*

next

case (*step* $T \ U$)

moreover then have *no-dup* (*trail* T)

using *rtrancpl-cdcl_{NOT}-no-dup*[of $S \ T$] *cdcl_{NOT}-NOT-all-inv-def* *inv*

rtrancpl-learn-or-forget-cdcl_{NOT} **by** *auto*

ultimately show $?_{\text{case}}$

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 *rtrancpl-learn-or-forget-cdcl_{NOT}* *cdcl_{NOT}-NOT-all-inv* *l-f* *inv* **by** *blast*

ultimately show $?_{\text{thesis}}$

using *dpll-bj-trail-mes-decreasing-prop*[of $T \ U \ A$, *OF* *dpll*] *finite*

unfolding *cdcl_{NOT}-NOT-all-inv-def* **by** *linarith*

qed

lemma *infinite-cdcl_{NOT}-exists-learn-and-forget-infinite-chain*:

assumes

```

 $\bigwedge i. \text{cdcl}_{NOT} (f\ i) (f(Suc\ i))$  and
 $inv: \text{cdcl}_{NOT-NOT-all-inv}\ A\ (f\ 0)$ 
shows  $\exists j. \forall i \geq j. \text{learn-or-forget}\ (f\ i) (f\ (Suc\ i))$ 
using assms
proof (induction ( $2 + \text{card}\ (\text{atms-of-ms}\ A)) \wedge (1 + \text{card}\ (\text{atms-of-ms}\ A))$ )
   $-\ \mu_C\ (1 + \text{card}\ (\text{atms-of-ms}\ A))\ (2 + \text{card}\ (\text{atms-of-ms}\ A))\ (\text{trail-weight}\ (f\ 0))$ 
  arbitrary: f
  rule: nat-less-induct-case
case (Suc n) note  $IH = \text{this}(1)$  and  $\mu = \text{this}(2)$  and  $\text{cdcl}_{NOT} = \text{this}(3)$  and  $inv = \text{this}(4)$ 
consider
  (dpll-end)  $\exists j. \forall i \geq j. \text{learn-or-forget}\ (f\ i) (f\ (Suc\ i))$ 
  | (dpll-more)  $\neg(\exists j. \forall i \geq j. \text{learn-or-forget}\ (f\ i) (f\ (Suc\ i)))$ 
by blast
then show ?case
proof cases
  case dpll-end
    then show ?thesis by auto
next
  case dpll-more
    then have  $j: \exists i. \neg \text{learn}\ (f\ i) (f\ (Suc\ i)) \wedge \neg \text{forget}_{NOT}\ (f\ i) (f\ (Suc\ i))$ 
    by blast
    obtain i where
       $\neg \text{learn}\ (f\ i) (f\ (Suc\ i)) \wedge \neg \text{forget}_{NOT}\ (f\ i) (f\ (Suc\ i))$  and
       $\forall k < i. \text{learn-or-forget}\ (f\ k) (f\ (Suc\ k))$ 
    proof  $-$ 
      obtain  $i_0$  where  $\neg \text{learn}\ (f\ i_0) (f\ (Suc\ i_0)) \wedge \neg \text{forget}_{NOT}\ (f\ i_0) (f\ (Suc\ i_0))$ 
      using j by auto
      then have  $\{i. i \leq i_0 \wedge \neg \text{learn}\ (f\ i) (f\ (Suc\ i)) \wedge \neg \text{forget}_{NOT}\ (f\ i) (f\ (Suc\ i))\} \neq \{\}$ 
      by auto
      let  $?I = \{i. i \leq i_0 \wedge \neg \text{learn}\ (f\ i) (f\ (Suc\ i)) \wedge \neg \text{forget}_{NOT}\ (f\ i) (f\ (Suc\ i))\}$ 
      let  $?i = \text{Min}\ ?I$ 
      have finite ?I
      by auto
      have  $\neg \text{learn}\ (f\ ?i) (f\ (Suc\ ?i)) \wedge \neg \text{forget}_{NOT}\ (f\ ?i) (f\ (Suc\ ?i))$ 
      using Min-in[OF (finite ?I) (?I ≠ {})] by auto
      moreover have  $\forall k < ?i. \text{learn-or-forget}\ (f\ k) (f\ (Suc\ k))$ 
      using Min.coboundedI[of {i. i ≤ i0 ∧ ¬ learn (f i) (f (Suc i)) ∧ ¬ forgetNOT (f i) (f (Suc i))}, simplified]
      by (meson ( $\neg \text{learn}\ (f\ i_0) (f\ (Suc\ i_0)) \wedge \neg \text{forget}_{NOT}\ (f\ i_0) (f\ (Suc\ i_0))$ ) less-imp-le dual-order.trans not-le)
      ultimately show ?thesis using that by blast
    qed
def  $g \equiv \lambda n. f\ (n + Suc\ i)$ 
have dpll-bj ( $f\ i$ ) ( $g\ 0$ )
  using  $\neg \text{learn}\ (f\ i) (f\ (Suc\ i)) \wedge \neg \text{forget}_{NOT}\ (f\ i) (f\ (Suc\ i))$  cdclNOT cdclNOT.cases
  g-def by auto
{
  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 rtrancIp.simps
     $\langle \forall k < i. \text{learn}\ (f\ k) (f\ (Suc\ k)) \vee \text{forget}_{NOT}\ (f\ k) (f\ (Suc\ k)) \rangle$ )
}

```

```

then have learn-or-forget** (f 0) (f i) by blast
then have (2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A))
  -  $\mu_C$  (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight (g 0))
  < (2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A))
  -  $\mu_C$  (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight (f 0))
using learn-or-forget-dpll- $\mu_C$ [of f 0 f i g 0 A] inv <dpll-bj (f i) (g 0)>
unfolding cdclNOT-NOT-all-inv-def by linarith

moreover have cdclNOT-i: cdclNOT** (f 0) (g 0)
using rtrancpl-learn-or-forget-cdclNOT[of f 0 f i] <learn-or-forget** (f 0) (f i)>
cdclNOT[of i] unfolding g-def by auto
moreover have  $\bigwedge i.$  cdclNOT (g i) (g (Suc i))
using cdclNOT g-def by auto
moreover have cdclNOT-NOT-all-inv A (g 0)
using inv cdclNOT-i rtrancpl-cdclNOT-trail-clauses-bound g-def cdclNOT-NOT-all-inv by auto
ultimately obtain j where j:  $\bigwedge i.$   $i \geq j \implies \text{learn-or-forget} (g i) (g (Suc i))$ 
using IH unfolding  $\mu$ [symmetric] by presburger
show ?thesis
proof
  {
    fix k
    assume  $k \geq j + \text{Suc } i$ 
    then have learn-or-forget (f k) (f (Suc k))
      using j[of k-Suc i] unfolding g-def by auto
  }
  then show  $\forall k \geq j + \text{Suc } i. \text{learn-or-forget} (f k) (f (Suc k))$ 
    by auto
qed
qed
next
case 0 note H = this(1) and cdclNOT = this(2) and inv = this(3)
show ?case
proof (rule ccontr)
assume  $\neg ?case$ 
then have j:  $\exists i. \neg \text{learn} (f i) (f (Suc i)) \wedge \neg \text{forget}_{NOT} (f i) (f (Suc i))$ 
by blast
obtain i where
   $\neg \text{learn} (f i) (f (Suc i)) \wedge \neg \text{forget}_{NOT} (f i) (f (Suc i))$  and
   $\forall k < i. \text{learn-or-forget} (f k) (f (Suc k))$ 
proof -
  obtain i0 where  $\neg \text{learn} (f i_0) (f (Suc i_0)) \wedge \neg \text{forget}_{NOT} (f i_0) (f (Suc i_0))$ 
    using j by auto
then have  $\{i. i \leq i_0 \wedge \neg \text{learn} (f i) (f (Suc i)) \wedge \neg \text{forget}_{NOT} (f i) (f (Suc i))\} \neq \{\}$ 
by auto
let ?I =  $\{i. i \leq i_0 \wedge \neg \text{learn} (f i) (f (Suc i)) \wedge \neg \text{forget}_{NOT} (f i) (f (Suc i))\}$ 
let ?i = Min ?I
have finite ?I
by auto
have  $\neg \text{learn} (f ?i) (f (Suc ?i)) \wedge \neg \text{forget}_{NOT} (f ?i) (f (Suc ?i))$ 
using Min-in[OF <finite ?I> <?I ≠ {}>] by auto
moreover have  $\forall k < ?i. \text{learn-or-forget} (f k) (f (Suc k))$ 
using Min.coboundedI[of  $\{i. i \leq i_0 \wedge \neg \text{learn} (f i) (f (Suc i)) \wedge \neg \text{forget}_{NOT} (f i) (f (Suc i))\}$ , simplified]
by (meson  $\neg \text{learn} (f i_0) (f (Suc i_0)) \wedge \neg \text{forget}_{NOT} (f i_0) (f (Suc i_0))$ ) 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 ≤ 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 rtrancpl.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-cdclNOT-no-learn-and-forget-infinite-chain:
  assumes
    no-infinite-lf: ∧ f j. ¬ (∀ i ≥ j. learn-or-forget (f i) (f (Suc i)))
  shows wf {(T, S). cdclNOT S T ∧ cdclNOT-NOT-all-inv A S} (is wf {(T, S). cdclNOT S T
    ∧ ?inv S})
  unfolding wf-iff-no-infinite-down-chain
proof (rule ccontr)
  assume ¬ ¬ (∃ f. ∀ i. (f (Suc i), f i) ∈ {(T, S). cdclNOT S T ∧ ?inv S})
  then obtain f where
    ∀ i. cdclNOT (f i) (f (Suc i)) ∧ ?inv (f i)
  by fast
  then have ∃ j. ∀ i ≥ j. learn-or-forget (f i) (f (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-trancpl-cdclNOT-trancpl-cdclNOT-and-inv:
  cdclNOT++ S T ∧ cdclNOT-NOT-all-inv A S ↔ (λ S T. cdclNOT S T ∧ cdclNOT-NOT-all-inv A
  S)++ S T
  (is ?A ∧ ?I ↔ ?B)
proof
  assume ?A ∧ ?I
  then have ?A and ?I by blast+
  then show ?B
    apply induction
    apply (simp add: trancpl.r-into-trancpl)
    by (metis (no-types, lifting) cdclNOT-NOT-all-inv trancpl.simps trancpl-into-rtrancpl)
next
  assume ?B
  then have ?A by induction auto
  moreover have ?I using ⟨?B⟩ trancplD by fastforce
  ultimately show ?A ∧ ?I by blast
qed

```

lemma *wf-tranclp-cdcl_{NOT}-no-learn-and-forget-infinite-chain*:

assumes

no-infinite-lf: $\bigwedge f j. \neg (\forall i \geq j. \text{learn-or-forget } (f i) (f (Suc i)))$

shows *wf* $\{(T, S). \text{cdcl}_{NOT}^{++} S T \wedge \text{cdcl}_{NOT}\text{-NOT-all-inv } A S\}$

using *wf-trancl*[*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

$\lambda C S. \text{distinct-mset } C \wedge \neg \text{tautology } C \wedge \text{learn-restrictions } C S \wedge$

$(\exists F K d F' C' L. \text{trail } S = F' @ \text{Marked } K () \# F \wedge C = C' + \{\#L\} \wedge F \models_{as} C \text{Not } C'$
 $\wedge C' + \{\#L\} \notin \# \text{clauses } S)$

$\lambda C S. \neg (\exists F' F K d L. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{as} C \text{Not } (C - \{\#L\}))$

```

 $\wedge$  forget-restrictions  $C$   $S$ 
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 clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool and
  learn-restrictions forget-restrictions :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool
begin

lemma cdclNOT-learn-all-induct[consumes 1, case-names dpll-bj learn forgetNOT]:
  fixes  $S$   $T$  :: 'st
  assumes cdclNOT  $S$   $T$  and
  dpll:  $\bigwedge T. \text{dpll-bj } S \ T \Longrightarrow P \ S \ T$  and
  learning:
     $\bigwedge C \ F \ K \ F' \ C' \ L \ T. \text{clauses } S \models_{pm} C$ 
     $\Longrightarrow \text{atms-of } C \subseteq \text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of } ' (\text{lits-of } (\text{trail } S))$ 
     $\Longrightarrow \text{distinct-mset } C \Longrightarrow \neg \text{tautology } C \Longrightarrow \text{learn-restrictions } C \ S$ 
     $\Longrightarrow \text{trail } S = F' @ \text{Marked } K \ () \ \# \ F \Longrightarrow C = C' + \{\#L\# \} \Longrightarrow F \models_{as} C \text{Not } C'$ 
     $\Longrightarrow C' + \{\#L\# \} \notin \text{clauses } S \Longrightarrow T \sim \text{add-cl}_{NOT} \ C \ S$ 
     $\Longrightarrow P \ S \ T$  and
  forgetting:  $\bigwedge C \ T. \text{clauses } S - \text{replicate-mset } (\text{count } (\text{clauses } S) \ C) \ C \models_{pm} C$ 
     $\Longrightarrow C \in \# \text{clauses } S$ 
     $\Longrightarrow \neg (\exists F' \ F \ K \ L. \text{trail } S = F' @ \text{Marked } K \ () \ \# \ F \wedge F \models_{as} C \text{Not } (C - \{\#L\# \}))$ 
     $\Longrightarrow T \sim \text{remove-cl}_{NOT} \ C \ S$ 
     $\Longrightarrow \text{forget-restrictions } C \ S \Longrightarrow P \ S \ T$ 
  shows  $P \ S \ T$ 
  using assms(1)
  apply (induction rule: cdclNOT.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.forgetNOT.cases[OF forget-ops-axioms] dest!: assms(4))
  done

lemma rtranclp-cdclNOT-inv:
  cdclNOT**  $S \ T \Longrightarrow \text{inv } S \Longrightarrow \text{inv } T$ 
  apply (induction rule: rtranclp-induct)
  apply simp
  using cdclNOT-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  $S$ )
     $\subseteq \text{simple-clss } (\text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of } ' (\text{lits-of } (\text{trail } S)))$ 
proof
  fix  $C$  assume  $C$ :  $C \in \text{set-mset } (\text{clauses } T - \text{clauses } S)$ 
  have distinct-mset  $C \neg \text{tautology } C$  using learn  $C$  n-d by (elim learnE; auto)+
  then have  $C \in \text{simple-clss } (\text{atms-of } C)$ 
  using distinct-mset-not-tautology-implies-in-simple-clss by blast

```

moreover have $\text{atms-of } C \subseteq \text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of } ' \text{ lits-of } (\text{trail } S)$
using $\text{learn } C \text{ n-d by } (\text{elim learnE}) (\text{auto simp: atms-of-ms-def atms-of-def image-Un true-annots-CNot-all-atms-defined})$
moreover have $\text{finite } (\text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of } ' \text{ lits-of } (\text{trail } S))$
by auto
ultimately show $C \in \text{simple-clss } (\text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of } ' \text{ lits-of } (\text{trail } S))$
using $\text{simple-clss-mono by } (\text{metis (no-types) insert-subset mk-disjoint-insert})$
qed

definition $\text{conflicting-bj-clss } S \equiv$
 $\{C + \{\#L\# \} \mid C \text{ L. } C + \{\#L\# \} \in \# \text{ clauses } S \wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$
 $\wedge (\exists F' K F. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{\text{as}} \text{CNot } C)\}$

lemma $\text{conflicting-bj-clss-remove-cl}_{\text{NOT}}[\text{simp}]$:
 $\text{conflicting-bj-clss } (\text{remove-cl}_{\text{NOT}} C S) = \text{conflicting-bj-clss } S - \{C\}$
unfolding $\text{conflicting-bj-clss-def by fastforce}$

lemma $\text{conflicting-bj-clss-add-cl}_{\text{NOT}}\text{-state-eq}$:
 $T \sim \text{add-cl}_{\text{NOT}} C' S \implies \text{no-dup } (\text{trail } S) \implies \text{conflicting-bj-clss } T$
 $= \text{conflicting-bj-clss } S$
 $\cup (\text{if } \exists C L. C' = C + \{\#L\# \} \wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$
 $\wedge (\exists F' K d F. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{\text{as}} \text{CNot } C)$
 $\text{then } \{C'\} \text{ else } \{\})$
unfolding $\text{conflicting-bj-clss-def by auto metis+}$

lemma $\text{conflicting-bj-clss-add-cl}_{\text{NOT}}$:
 $\text{no-dup } (\text{trail } S) \implies$
 $\text{conflicting-bj-clss } (\text{add-cl}_{\text{NOT}} C' S)$
 $= \text{conflicting-bj-clss } S$
 $\cup (\text{if } \exists C L. C' = C + \{\#L\# \} \wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$
 $\wedge (\exists F' K d F. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{\text{as}} \text{CNot } C)$
 $\text{then } \{C'\} \text{ else } \{\})$
using $\text{conflicting-bj-clss-add-cl}_{\text{NOT}}\text{-state-eq by auto}$

lemma $\text{conflicting-bj-clss-incl-clauses}$:
 $\text{conflicting-bj-clss } S \subseteq \text{set-mset } (\text{clauses } S)$
unfolding $\text{conflicting-bj-clss-def by auto}$

lemma $\text{finite-conflicting-bj-clss}[\text{simp}]$:
 $\text{finite } (\text{conflicting-bj-clss } S)$
using $\text{conflicting-bj-clss-incl-clauses[of } S] \text{ rev-finite-subset by blast}$

lemma $\text{learn-conflicting-increasing}$:
 $\text{no-dup } (\text{trail } S) \implies \text{learn } S T \implies \text{conflicting-bj-clss } S \subseteq \text{conflicting-bj-clss } T$
apply (elim learnE)
by $(\text{subst conflicting-bj-clss-add-cl}_{\text{NOT}}\text{-state-eq[of } T]) \text{ auto}$

abbreviation $\text{conflicting-bj-clss-yet } b S \equiv$
 $3 \wedge b - \text{card } (\text{conflicting-bj-clss } S)$

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 $\text{do-not-forget-before-backtrack-rule-clause-learned-clause-untouched}$:
assumes $\text{forget}_{\text{NOT}} S T$

shows *conflicting-bj-clss* $S = \text{conflicting-bj-clss } T$
using *assms* **apply** *induction*
unfolding *conflicting-bj-clss-def*
by (*metis* (*no-types*, *lifting*) *Diff-insert-absorb* *Set.set-insert* *clauses-remove-clss_{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-clss_{NOT}*)

lemma *forget- μ_L -decrease*:
assumes *forget_{NOT}*: *forget_{NOT} S T*
shows $(\mu_L \ b \ T, \mu_L \ b \ S) \in \text{less-than} \text{ } <*\text{lex}*> \text{ less-than}$
proof –
have *card* (*set-mset* (*clauses T*)) < *card* (*set-mset* (*clauses S*))
using *forget_{NOT}* **apply** *induction*
by (*metis* *card-Diff1-less* *clauses-remove-clss_{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 $(\mu_L \ (\text{card } A) \ T, \mu_L \ (\text{card } A) \ S) \in \text{less-than} \text{ } <*\text{lex}*> \text{ less-than}$

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 $\exists: (\exists::\text{nat}) \wedge \text{card} \ (\text{atms-of-msu} \ (\text{clauses } T) \cup \text{atm-of ' lits-of} \ (\text{trail } T))$
 $= \exists \wedge \text{card} \ (\text{atms-of-msu} \ (\text{clauses } S) \cup \text{atm-of ' lits-of} \ (\text{trail } S))$
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* \neq *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* $\models_{\text{as}} C \text{Not } C'$ **and**
C-S: *C' + {#L#}* $\notin \#$ *clauses S*

by *blast*
 moreover have *distinct-mset* $C \neg \text{tautology } C$ using *inv* by *blast* +
 ultimately have $C' + \{\#L\# \} \in \text{conflicting-bj-clss } T$
 using *T n-d unfolding conflicting-bj-clss-def* by *fastforce*
 moreover have $C' + \{\#L\# \} \notin \text{conflicting-bj-clss } S$
 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-clss_{NOT}*)
 ultimately have *card* (*conflicting-bj-clss* *T*) \geq *card* (*conflicting-bj-clss* *S*)
 using *card-mono* by *blast*

 moreover
 have *fin'*: *finite* (*atms-of-msu* (*clauses* *T*) \cup *atm-of* ' *lits-of* (*trail* *T*))
 by *auto*
 have 1: *atms-of-ms* (*conflicting-bj-clss* *T*) \subseteq *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*
 \subseteq *simple-clss* (*atms-of-msu* (*clauses* *T*) \cup *atm-of* ' *lits-of* (*trail* *T*))
 by *standard* (*meson* 1 2 *fin'* \langle *finite* (*conflicting-bj-clss* *T*) \rangle *simple-clss-mono*
distinct-mset-set-def simplified-in-simple-clss subsetCE sup.coboundedI1)
 moreover
 then have $\# : 3 \wedge \text{card} (\text{atms-of-msu} (\text{clauses } T) \cup \text{atm-of ' lits-of } (\text{trail } T))$
 $\geq \text{card} (\text{conflicting-bj-clss } T)$
 by (*meson* *Nat.le-trans simple-clss-card simple-clss-finite card-mono fin'*)
 have *atms-of-msu* (*clauses* *T*) \cup *atm-of* ' *lits-of* (*trail* *T*) $\subseteq A$
 using *learnE[OF learnST] A* by *simp*
 then have $3 \wedge (\text{card } A) \geq \text{card} (\text{conflicting-bj-clss } T)$
 using $\#$ *fin-A* by (*meson simple-clss-card simple-clss-finite*
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* $\langle \text{conflicting-bj-clss } S \neq \text{conflicting-bj-clss } T \rangle$
 $\langle \text{conflicting-bj-clss } S \subseteq \text{conflicting-bj-clss } T \rangle$
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*) \subseteq *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**

$$\begin{aligned}
 \mu_{CDCL} A T \equiv & ((2 + \text{card} (\text{atms-of-ms } A)) \wedge (1 + \text{card} (\text{atms-of-ms } A))) \\
 & - \mu_C (1 + \text{card} (\text{atms-of-ms } A)) (2 + \text{card} (\text{atms-of-ms } A)) (\text{trail-weight } T), \\
 & \text{conflicting-bj-clss-yet } (\text{card} (\text{atms-of-ms } A)) T, \text{card} (\text{set-mset } (\text{clauses } T)))
 \end{aligned}$$

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- μ_L -decrease[OF learn -] atm-clss atm-lits fin-A n-d unfolding S μ_{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- μ_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 $\mu_C' :: 'v \text{ literal multiset set} \Rightarrow 'st \Rightarrow \text{nat}$ **where**

$\mu_C' A T \equiv \mu_C (1 + \text{card} (\text{atms-of-ms } A)) (2 + \text{card} (\text{atms-of-ms } A)) (\text{trail-weight } T)$

definition $\mu_{CDCL}' :: 'v \text{ literal multiset set} \Rightarrow 'st \Rightarrow \text{nat}$ **where**

$\mu_{CDCL}' A T \equiv$

$((2 + \text{card} (\text{atms-of-ms } A)) \wedge (1 + \text{card} (\text{atms-of-ms } A)) - \mu_C' A T) * (1 + 3^{\text{card} (\text{atms-of-ms } A)}) *$

2

$+ \text{conflicting-bj-clss-yet} (\text{card} (\text{atms-of-ms } A)) T * 2$

$+ \text{card} (\text{set-mset} (\text{clauses } T))$

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

$atms\text{-}trail: atm\text{-}of \text{ ' } lits\text{-}of (trail\ S) \subseteq atms\text{-}of\text{-}ms\ A$ **and**
 $n\text{-}d: no\text{-}dup (trail\ S)$ **and**
 $fin\text{-}A: finite\ A$
shows $\mu_{CDCL}'\ A\ T < \mu_{CDCL}'\ A\ S$
using $assms(1)$
proof (*induction rule: cdcl_{NOT}-learn-all-induct*)
case ($dpll\text{-}bj\ T$)
then have $(2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ T$
 $< (2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ S$
using $dpll\text{-}bj\text{-}trail\text{-}mes\text{-}decreasing\text{-}prop\ fin\text{-}A\ inv\ n\text{-}d\ atms\text{-}clss\ atms\text{-}trail$
unfolding $\mu_C'\text{-}def$ **by** $blast$
then have $XX: ((2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ T) + 1$
 $\leq (2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ S$
by $auto$
from $mult\text{-}le\text{-}mono1[OF\ this, of\ (1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A))]$
have $((2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ T) *$
 $(1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A)) + (1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A))$
 $\leq ((2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ S)$
 $* (1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A))$
unfolding $Nat.add\text{-}mult\text{-}distrib$
by $presburger$
moreover
have $cl\text{-}T\text{-}S: clauses\ T = clauses\ S$
using $dpll\text{-}bj.hyps\ inv\ dpll\text{-}bj\text{-}clauses$ **by** $auto$
have $conflicting\text{-}bj\text{-}clss\text{-}yet\ (card\ (atms\text{-}of\text{-}ms\ A))\ S < 1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A)$
by $simp$
ultimately have $((2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ T)$
 $* (1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A)) + conflicting\text{-}bj\text{-}clss\text{-}yet\ (card\ (atms\text{-}of\text{-}ms\ A))\ T$
 $< ((2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ S) * (1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A))$
 $A))$
by $linarith$
then have $((2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ T)$
 $* (1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A))$
 $+ conflicting\text{-}bj\text{-}clss\text{-}yet\ (card\ (atms\text{-}of\text{-}ms\ A))\ T$
 $< ((2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ S)$
 $* (1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A))$
 $+ conflicting\text{-}bj\text{-}clss\text{-}yet\ (card\ (atms\text{-}of\text{-}ms\ A))\ S$
by $linarith$
then have $((2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ T)$
 $* (1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A)) * 2$
 $+ conflicting\text{-}bj\text{-}clss\text{-}yet\ (card\ (atms\text{-}of\text{-}ms\ A))\ T * 2$
 $< ((2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A)) - \mu_C'\ A\ S)$
 $* (1 + 3 \wedge card\ (atms\text{-}of\text{-}ms\ A)) * 2$
 $+ conflicting\text{-}bj\text{-}clss\text{-}yet\ (card\ (atms\text{-}of\text{-}ms\ A))\ S * 2$
by $linarith$
then show $?case$ **unfolding** $\mu_{CDCL}'\text{-}def\ cl\text{-}T\text{-}S$ **by** $presburger$
next
case ($learn\ C\ F'\ K\ F\ C'\ L\ T$) **note** $clss\text{-}S\text{-}C = this(1)$ **and** $atms\text{-}C = this(2)$ **and** $dist = this(3)$
and $tauto = this(4)$ **and** $learn\text{-}restr = this(5)$ **and** $tr\text{-}S = this(6)$ **and** $C' = this(7)$ **and**
 $F\text{-}C = this(8)$ **and** $C\text{-}new = this(9)$ **and** $T = this(10)$
have $insert\ C\ (conflicting\text{-}bj\text{-}clss\ S) \subseteq simple\text{-}clss\ (atms\text{-}of\text{-}ms\ A)$
proof –
have $C \in simple\text{-}clss\ (atms\text{-}of\text{-}ms\ A)$
by ($metis\ (no\text{-}types, hide\text{-}lams)\ Un\text{-}subset\text{-}iff\ atms\text{-}of\text{-}ms\text{-}finite\ simple\text{-}clss\text{-}mono$
 $contra\text{-}subsetD\ dist\ distinct\text{-}mset\text{-}not\text{-}tautology\text{-}implies\text{-}in\text{-}simple\text{-}clss$

```

    dual-order.trans fin-A atms-C atms-clss atms-trail tauto)
moreover have conflicting-bj-clss  $S \subseteq \text{simple-clss } (\text{atms-of-ms } A)$ 
unfolding conflicting-bj-clss-def
proof
  fix  $x :: 'v$  literal multiset
  assume  $x \in \{C + \{\#L\# \} \mid C \text{ L. } C + \{\#L\# \} \in \# \text{ clauses } S$ 
     $\wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$ 
     $\wedge (\exists F' K F. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{as} C \text{Not } C)\}$ 
  then have  $\exists m \text{ l. } x = m + \{\#l\# \} \wedge m + \{\#l\# \} \in \# \text{ clauses } S$ 
     $\wedge \text{distinct-mset } (m + \{\#l\# \}) \wedge \neg \text{tautology } (m + \{\#l\# \})$ 
     $\wedge (\exists ms \text{ l msa. trail } S = ms @ \text{Marked } l () \# msa \wedge msa \models_{as} C \text{Not } m)$ 
  by blast
  then show  $x \in \text{simple-clss } (\text{atms-of-ms } A)$ 
  by (meson atms-clss atms-of-atms-of-ms-mono atms-of-ms-finite simple-clss-mono
    distinct-mset-not-tautology-implies-in-simple-clss fin-A finite-subset
    mem-set-mset-iff set-rev-mp)
qed
ultimately show ?thesis
by auto
qed
then have  $\text{card } (\text{insert } C (\text{conflicting-bj-clss } S)) \leq 3 \wedge (\text{card } (\text{atms-of-ms } A))$ 
by (meson Nat.le-trans atms-of-ms-finite simple-clss-card simple-clss-finite
  card-mono fin-A)
moreover have [simp]:  $\text{card } (\text{insert } C (\text{conflicting-bj-clss } S))$ 
  =  $\text{Suc } (\text{card } ((\text{conflicting-bj-clss } S)))$ 
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]:  $\text{conflicting-bj-clss } (\text{add-cl}_{NOT} C S) = \text{conflicting-bj-clss } S \cup \{C\}$ 
  using  $\text{dist tauto } F\text{-}C \text{ n-d}$  by (subst conflicting-bj-clss-add-clNOT)
  (force simp add: ac-simps  $C'$  tr-S)+
ultimately have [simp]:  $\text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) S$ 
  =  $\text{Suc } (\text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) (\text{add-cl}_{NOT} C S))$ 
  by simp
have 1:  $\text{clauses } T = \text{clauses } (\text{add-cl}_{NOT} C S)$  using  $T$  by auto
have 2:  $\text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) T$ 
  =  $\text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) (\text{add-cl}_{NOT} C S)$ 
  using  $T$  unfolding conflicting-bj-clss-def by auto
have 3:  $\mu_{C'} A T = \mu_{C'} A (\text{add-cl}_{NOT} C S)$ 
  using  $T$  unfolding  $\mu_{C'}$ -def by auto
have  $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_{C'} A (\text{add-cl}_{NOT} C S))$ 
  *  $(1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) * 2$ 
  =  $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_{C'} A S)$ 
  *  $(1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) * 2$ 
  using  $\text{n-d unfolding } \mu_{C'}$ -def by auto
moreover
  have  $\text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) (\text{add-cl}_{NOT} C S)$ 
    * 2
    +  $\text{card } (\text{set-mset } (\text{clauses } (\text{add-cl}_{NOT} C S)))$ 
    <  $\text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) S * 2$ 
    +  $\text{card } (\text{set-mset } (\text{clauses } S))$ 
  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  $T = \text{this}(4)$ 
have [simp]:  $\mu_{C'} A (\text{remove-cl}_{NOT} C S) = \mu_{C'} A S$ 

```

unfolding μ_C' -def by auto
 have forget_{NOT} S T
 apply (rule forget_{NOT}.intros) using forget_{NOT} 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-cls_{NOT} finite-set-mset forget_{NOT}.hyps(2)
 mem-set-mset-iff order-refl set-mset-minus-replicate-mset(1) state-eq_{NOT}-clauses)
 ultimately show ?case unfolding μ_{CDCL}' -def
 by (metis (no-types) T $\langle \mu_C' A \text{ (remove-cls}_{NOT} C S) = \mu_C' A S \rangle$ add-le-cancel-left
 μ_C' -def not-le state-eq_{NOT}-trail)
 qed

lemma cdcl_{NOT}-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
 fin-A[simp]: finite A
 shows set-mset (clauses T) \subseteq set-mset (clauses S) \cup simple-clss A
 using assms
 proof (induction rule: cdcl_{NOT}-learn-all-induct)
 case dpll-bj
 then show ?case using dpll-bj-clauses by simp
 next
 case forget_{NOT}
 then show ?case using clauses-remove-cls_{NOT} unfolding state-eq_{NOT}-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 simple-clss (atms-of C) \subseteq simple-clss A
 by (simp add: simple-clss-mono)
 then have C \in simple-clss A
 using finite dist tauto
 by (auto dest: distinct-mset-not-tautology-implies-in-simple-clss)
 then show ?case using T n-d by auto
 qed

lemma rtrancpl-cdcl_{NOT}-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 set-mset (clauses T) \subseteq set-mset (clauses S) \cup simple-clss A
 using assms(1-5)
 proof induction
 case base
 then show ?case by simp

next

case (*step* $T\ U$) **note** $st = \text{this}(1)$ **and** $cdcl_{NOT} = \text{this}(2)$ **and** $IH = \text{this}(3)[OF\ \text{this}(4-7)]$ **and**
 $inv = \text{this}(4)$ **and** $atms\text{-}clss\text{-}S = \text{this}(5)$ **and** $atms\text{-}trail\text{-}S = \text{this}(6)$ **and** $finite\text{-}cls\text{-}S = \text{this}(7)$
have $inv\ T$
 using $rtranclp\text{-}cdcl_{NOT}\text{-}inv\ st\ inv$ **by** *blast*
moreover **have** $atms\text{-}of\text{-}msu\ (clauses\ T) \subseteq A$ **and** $atm\text{-}of\ ' (lits\text{-}of\ (trail\ T)) \subseteq A$
 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** $no\text{-}dup\ (trail\ T)$
 using $rtranclp\text{-}cdcl_{NOT}\text{-}no\text{-}dup[OF\ st\ \langle inv\ S \rangle\ n\text{-}d]$ **by** *simp*
ultimately **have** $set\text{-}mset\ (clauses\ U) \subseteq set\text{-}mset\ (clauses\ T) \cup simple\text{-}clss\ A$
 using $cdcl_{NOT}\ finite\ n\text{-}d$ **by** (*auto simp: cdcl_{NOT}-clauses-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**
 $atms\text{-}of\text{-}msu\ (clauses\ S) \subseteq A$ **and**
 $atm\text{-}of\ '(lits\text{-}of\ (trail\ S)) \subseteq A$ **and**
 $n\text{-}d$: $no\text{-}dup\ (trail\ S)$ **and**
 $finite$: $finite\ A$
shows $card\ (set\text{-}mset\ (clauses\ T)) \leq card\ (set\text{-}mset\ (clauses\ S)) + 3 \wedge (card\ A)$
using $rtranclp\text{-}cdcl_{NOT}\text{-}clauses\text{-}bound[OF\ assms]\ finite$ **by** (*meson Nat.le-trans simple-clss-card simple-clss-finite card-Un-le card-mono finite-UnI finite-set-mset nat-add-left-cancel-le*)

lemma $rtranclp\text{-}cdcl_{NOT}\text{-}card\text{-}clauses\text{-}bound'$:

assumes
 $cdcl_{NOT}^{**}\ S\ T$ **and**
 $inv\ S$ **and**
 $atms\text{-}of\text{-}msu\ (clauses\ S) \subseteq A$ **and**
 $atm\text{-}of\ '(lits\text{-}of\ (trail\ S)) \subseteq A$ **and**
 $n\text{-}d$: $no\text{-}dup\ (trail\ S)$ **and**
 $finite$: $finite\ A$
shows $card\ \{C \mid C. C \in \# clauses\ T \wedge (tautology\ C \vee \neg distinct\text{-}mset\ C)\}$
 $\leq card\ \{C \mid C. C \in \# clauses\ S \wedge (tautology\ C \vee \neg distinct\text{-}mset\ C)\} + 3 \wedge (card\ A)$
 (*is card ?T ≤ card ?S + -*)

using $rtranclp\text{-}cdcl_{NOT}\text{-}clauses\text{-}bound[OF\ assms]\ finite$

proof –

have $?T \subseteq ?S \cup simple\text{-}clss\ A$
 using $rtranclp\text{-}cdcl_{NOT}\text{-}clauses\text{-}bound[OF\ assms]$ **by** *force*
then have $card\ ?T \leq card\ (?S \cup simple\text{-}clss\ A)$
 using $finite$ **by** (*simp add: assms(5) simple-clss-finite card-mono*)
then show *?thesis*
 by (*meson le-trans simple-clss-card card-Un-le local.finite nat-add-left-cancel-le*)

qed

lemma $rtranclp\text{-}cdcl_{NOT}\text{-}card\text{-}simple\text{-}clauses\text{-}bound$:

assumes
 $cdcl_{NOT}^{**}\ S\ T$ **and**
 $inv\ S$ **and**
 $atms\text{-}of\text{-}msu\ (clauses\ S) \subseteq A$ **and**
 $atm\text{-}of\ '(lits\text{-}of\ (trail\ S)) \subseteq A$ **and**

n-d: no-dup (trail S) and
finite: finite A
shows $\text{card } (\text{set-mset } (\text{clauses } T))$
 $\leq \text{card } \{C. C \in \# \text{ clauses } S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\} + 3 \wedge (\text{card } A)$
(is card ?T ≤ card ?S + -)
using $\text{rtrancpl-cdcl}_{NOT}\text{-clauses-bound}[OF \text{ assms}] \text{ finite}$
proof –
have $\bigwedge x. x \in \# \text{ clauses } T \implies \neg \text{tautology } x \implies \text{distinct-mset } x \implies x \in \text{simple-clss } A$
using $\text{rtrancpl-cdcl}_{NOT}\text{-clauses-bound}[OF \text{ assms}]$ **by** (*metis (no-types, hide-lams) Un-iff assms(3)*
atms-of-atms-of-ms-mono simple-clss-mono contra-subsetD
distinct-mset-not-tautology-implies-in-simple-clss local.finite mem-set-mset-iff
subset-trans)
then have $\text{set-mset } (\text{clauses } T) \subseteq ?S \cup \text{simple-clss } A$
using $\text{rtrancpl-cdcl}_{NOT}\text{-clauses-bound}[OF \text{ assms}]$ **by** *auto*
then have $\text{card}(\text{set-mset } (\text{clauses } T)) \leq \text{card } (?S \cup \text{simple-clss } A)$
using *finite* **by** (*simp add: assms(5) simple-clss-finite card-mono*)
then show *?thesis*
by (*meson le-trans simple-clss-card card-Un-le local.finite nat-add-left-cancel-le*)
qed

definition $\mu_{CDCL}'\text{-bound} :: 'v \text{ literal multiset set} \Rightarrow 'st \Rightarrow \text{nat}$ **where**
 $\mu_{CDCL}'\text{-bound } A \ S =$
 $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))) * (1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) * 2$
 $+ 2 * 3 \wedge (\text{card } (\text{atms-of-ms } A))$
 $+ \text{card } \{C. C \in \# \text{ clauses } S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\} + 3 \wedge (\text{card } (\text{atms-of-ms } A))$

lemma $\mu_{CDCL}'\text{-bound-reduce-trail-to}_{NOT}[\text{simp}]$:
 $\mu_{CDCL}'\text{-bound } A \ (\text{reduce-trail-to}_{NOT} \ M \ S) = \mu_{CDCL}'\text{-bound } A \ S$
unfolding $\mu_{CDCL}'\text{-bound-def}$ **by** *auto*

lemma $\text{rtrancpl-cdcl}_{NOT}\text{-}\mu_{CDCL}'\text{-bound-reduce-trail-to}_{NOT}$:

assumes
*cdcl_{NOT}** S T and*
inv S and
atms-of-msu (clauses S) ⊆ atms-of-ms A and
atm-of '(lits-of (trail S)) ⊆ atms-of-ms A and
n-d: no-dup (trail S) and
finite: finite (atms-of-ms A) and
U: U ~ reduce-trail-to_{NOT} M T

shows $\mu_{CDCL}' A \ U \leq \mu_{CDCL}'\text{-bound } A \ S$

proof –
have $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A \ U)$
 $\leq (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$
by *auto*
then have $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) - \mu_C' A \ U)$
 $* (1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) * 2$
 $\leq (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) * (1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) * 2$
using *mult-le-mono1* **by** *blast*
moreover
have $\text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) \ T * 2 \leq 2 * 3 \wedge \text{card } (\text{atms-of-ms } A)$
by *linarith*
moreover have $\text{card } (\text{set-mset } (\text{clauses } U))$
 $\leq \text{card } \{C. C \in \# \text{ clauses } S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\} + 3 \wedge \text{card } (\text{atms-of-ms } A)$
using $\text{rtrancpl-cdcl}_{NOT}\text{-card-simple-clauses-bound}[OF \text{ assms}(1-6)] \ U$ **by** *auto*
ultimately show *?thesis*

unfolding $\mu_{CDCL}'\text{-def}$ $\mu_{CDCL}'\text{-bound-def}$ **by** *linarith*
qed

lemma *rtrancpl-cdcl_{NOT}- μ_{CDCL}' -bound*:

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)

shows $\mu_{CDCL}' A T \leq \mu_{CDCL}'\text{-bound } A S$

proof –

have $\mu_{CDCL}' A$ (*reduce-trail-to_{NOT}* (*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** *rtrancpl-cdcl_{NOT}- μ_{CDCL}' -bound-reduce-trail-to_{NOT}*[*OF* *assms*, *of* - *trail* T]
state-eq_{NOT}-ref **by** *fastforce*

qed

lemma *rtrancpl- μ_{CDCL}' -bound-decreasing*:

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[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** $t-d$: *tautology* $C \vee \neg \text{distinct-mset } C$
by *auto*

then have $C \notin \text{simple-clss}$ (*atms-of-ms* A)

by (*auto* *dest*: *simple-clssE*)

then show $C \in ?S$

using $C-T$ *rtrancpl-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} :: $'st \Rightarrow 'st \Rightarrow \text{bool}$ **and**


```

    restart :: 'st ⇒ 'st ⇒ bool
begin
inductive cdclNOT-raw-restart :: 'st ⇒ 'st ⇒ bool where
cdclNOT S T ⇒ cdclNOT-raw-restart S T |
restart S T ⇒ cdclNOT-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 ⇒ ('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
    backjump-conds :: 'v clause ⇒ 'v clause ⇒ 'v literal ⇒ 'st ⇒ 'st ⇒ bool and
    learn-cond forget-cond :: 'v clause ⇒ 'st ⇒ bool
begin

lemma cdclNOT-iff-cdclNOT-raw-restart-no-restarts:
  cdclNOT S T ⇔ restart-ops.cdclNOT-raw-restart cdclNOT (λ-. False) S T
  (is ?C S T ⇔ ?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 cdclNOT-cdclNOT-raw-restart:
  cdclNOT S T ⇒ restart-ops.cdclNOT-raw-restart cdclNOT 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 $cdcl_{NOT}$ -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 μ -bound taking the same parameter as μ and the initial state of the considered $cdcl_{NOT}$ chain.

```

locale  $cdcl_{NOT}$ -increasing-restarts-ops =
  restart-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
   $cdcl_{NOT}$ -inv :: 'st  $\Rightarrow$  bool and
   $\mu$ -bound :: 'bound  $\Rightarrow$  'st  $\Rightarrow$  nat
assumes
  f: unbounded f and
  f-ge-1:  $\bigwedge n. n \geq 1 \Rightarrow f\ n \neq 0$  and
  bound-inv:  $\bigwedge A\ S\ T. cdcl_{NOT}$ -inv S  $\Rightarrow$  bound-inv A S  $\Rightarrow$   $cdcl_{NOT}$  S T  $\Rightarrow$  bound-inv A T and
   $cdcl_{NOT}$ -measure:  $\bigwedge A\ S\ T. cdcl_{NOT}$ -inv S  $\Rightarrow$  bound-inv A S  $\Rightarrow$   $cdcl_{NOT}$  S T  $\Rightarrow$   $\mu\ A\ T < \mu$ 
A S and
  measure-bound2:  $\bigwedge A\ T\ U. cdcl_{NOT}$ -inv T  $\Rightarrow$  bound-inv A T  $\Rightarrow$   $cdcl_{NOT}^{**}$  T U
     $\Rightarrow \mu\ A\ U \leq \mu$ -bound A T and
  measure-bound4:  $\bigwedge A\ T\ U. cdcl_{NOT}$ -inv T  $\Rightarrow$  bound-inv A T  $\Rightarrow$   $cdcl_{NOT}^{**}$  T U
     $\Rightarrow \mu$ -bound A U  $\leq \mu$ -bound A T and
   $cdcl_{NOT}$ -restart-inv:  $\bigwedge A\ U\ V. cdcl_{NOT}$ -inv U  $\Rightarrow$  restart U V  $\Rightarrow$  bound-inv A U  $\Rightarrow$  bound-inv
A V
and
  exists-bound:  $\bigwedge R\ S. cdcl_{NOT}$ -inv R  $\Rightarrow$  restart R S  $\Rightarrow$   $\exists A. bound$ -inv A S and
   $cdcl_{NOT}$ -inv:  $\bigwedge S\ T. cdcl_{NOT}$ -inv S  $\Rightarrow$   $cdcl_{NOT}$  S T  $\Rightarrow$   $cdcl_{NOT}$ -inv T and
   $cdcl_{NOT}$ -inv-restart:  $\bigwedge S\ T. cdcl_{NOT}$ -inv S  $\Rightarrow$  restart S T  $\Rightarrow$   $cdcl_{NOT}$ -inv T
begin

```

lemma $cdcl_{NOT}$ - $cdcl_{NOT}$ -inv:

```

assumes
  ( $cdcl_{NOT} \sim n$ ) S T and
   $cdcl_{NOT}$ -inv S
shows  $cdcl_{NOT}$ -inv T
using assms by (induction n arbitrary: T) (auto intro: bound-inv cdcl_{NOT}-inv)

```

lemma $cdcl_{NOT}$ -bound-inv:

```

assumes
  ( $cdcl_{NOT} \sim n$ ) 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 $rtrancp$ - $cdcl_{NOT}$ - $cdcl_{NOT}$ -inv:

```

assumes
   $cdcl_{NOT}^{**} S T$  and
   $cdcl_{NOT-inv} S$ 
shows  $cdcl_{NOT-inv} T$ 
using assms by induction (auto intro: cdclNOT-inv)

lemma rtrancpl-cdclNOT-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 rtrancpl-cdclNOT-cdclNOT-inv)

lemma cdclNOT-comp-n-le:
assumes
   $(cdcl_{NOT} \sim (Suc\ n)) S T$  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 cdclNOT-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  $S-U: (cdcl_{NOT} \sim (Suc\ n)) S U$  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-cdclNOT:
   $wf \{(T, S). cdcl_{NOT} S T \wedge cdcl_{NOT-inv} S \wedge bound-inv A S\}$  (is  $wf\ ?A$ )
  apply (rule wfP-if-measure2[of - -  $\mu A$ ])
  using cdclNOT-comp-n-le[of 0 - - A] by auto

lemma rtrancpl-cdclNOT-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  $cdcl_{NOT} = this(2)$  and
   $b-inv = this(4)$  and  $c-inv = this(5)$ 

```

have *bound-inv* $A \ T$
by (*meson* *cdcl_{NOT}-bound-inv* *rtrancp-imp-relpowp* *st* *step.prem*s)
moreover have *cdcl_{NOT}-inv* T
using *c-inv* *rtrancp-cdcl_{NOT}-cdcl_{NOT}-inv* *st* **by** *blast*
ultimately have $\mu \ A \ U < \mu \ A \ T$ **using** *cdcl_{NOT}-measure*[*OF* - - *cdcl_{NOT}*] **by** *auto*
then show *?case* **using** *IH* **by** *linarith*
qed

lemma *cdcl_{NOT}-comp-bounded*:

assumes
bound-inv $A \ S$ **and** *cdcl_{NOT}-inv* S **and** $m \geq 1 + \mu \ A \ S$
shows $\neg(\text{cdcl}_{NOT} \sim^m) \ S \ T$
using *assms* *cdcl_{NOT}-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: $(\text{cdcl}_{NOT} \sim^m) \ S \ T \implies m \geq f \ n \implies \text{restart} \ T \ U$
 $\implies \text{cdcl}_{NOT}\text{-restart} \ (S, n) \ (U, \text{Suc } n) \mid$
restart-full: *full1* *cdcl_{NOT}* $S \ T \implies \text{cdcl}_{NOT}\text{-restart} \ (S, n) \ (T, \text{Suc } n)$

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*:

cdcl_{NOT}-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-rtrancp*)

then have *cdcl_{NOT}-raw-restart*** $S \ T$ **using** *cdcl_{NOT}-raw-restart.intros*(1)
rtrancp-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)
rtrancp-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* *rtrancp-unfold* *fstI* *full1-def* *rtrancp-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 $cdcl_{NOT}\text{-inv}$ ($fst\ T$)
using *assms* **apply** *induction*
apply (*metis* $cdcl_{NOT}\text{-}cdcl_{NOT}\text{-inv}$ $cdcl_{NOT}\text{-inv}\text{-restart}$ $fst\text{-conv}$)
apply (*metis* $fstI$ *full-def* *full-unfold* $rtranclp\text{-}cdcl_{NOT}\text{-}cdcl_{NOT}\text{-inv}$)
done

lemma $rtranclp\text{-}cdcl_{NOT}\text{-with-restart}\text{-}cdcl_{NOT}\text{-inv}$:

assumes
 $cdcl_{NOT}\text{-restart}^{**}\ S\ T$ **and**
 $cdcl_{NOT}\text{-inv}$ ($fst\ S$)
shows $cdcl_{NOT}\text{-inv}$ ($fst\ T$)
using *assms* **by** *induction* (*auto* *intro*: $cdcl_{NOT}\text{-with-restart}\text{-}cdcl_{NOT}\text{-inv}$)

lemma $rtranclp\text{-}cdcl_{NOT}\text{-with-restart}\text{-bound}\text{-inv}$:

assumes
 $cdcl_{NOT}\text{-restart}^{**}\ S\ T$ **and**
 $cdcl_{NOT}\text{-inv}$ ($fst\ S$) **and**
 $bound\text{-inv}\ A$ ($fst\ S$)
shows $bound\text{-inv}\ A$ ($fst\ T$)
using *assms* **apply** *induction*
apply (*simp* *add*: $cdcl_{NOT}\text{-}cdcl_{NOT}\text{-inv}$ $cdcl_{NOT}\text{-with-restart}\text{-bound}\text{-inv}$)
using $cdcl_{NOT}\text{-with-restart}\text{-bound}\text{-inv}$ $rtranclp\text{-}cdcl_{NOT}\text{-with-restart}\text{-}cdcl_{NOT}\text{-inv}$ **by** *blast*

lemma $cdcl_{NOT}\text{-with-restart}\text{-increasing-number}$:

$cdcl_{NOT}\text{-restart}\ S\ T \implies snd\ T = 1 + snd\ S$
by (*induction* *rule*: $cdcl_{NOT}\text{-restart.induct}$) *auto*
end

locale $cdcl_{NOT}\text{-increasing-restarts} =$

$cdcl_{NOT}\text{-increasing-restarts-ops}$ $restart\ cdcl_{NOT}\ f\ bound\text{-inv}\ \mu\ cdcl_{NOT}\text{-inv}\ \mu\text{-bound}$
for

$trail :: 'st \Rightarrow ('v, unit, unit)\ marked\text{-lits}$ **and**
 $clauses :: 'st \Rightarrow 'v\ clauses$ **and**
 $prepend\text{-}trail :: ('v, unit, unit)\ marked\text{-lit} \Rightarrow 'st \Rightarrow 'st$ **and**
 $tl\text{-}trail :: 'st \Rightarrow 'st$ **and**
 $add\text{-}cls_{NOT}\ remove\text{-}cls_{NOT} :: 'v\ clause \Rightarrow 'st \Rightarrow 'st$ **and**
 $f :: nat \Rightarrow nat$ **and**
 $restart :: 'st \Rightarrow 'st \Rightarrow bool$ **and**
 $bound\text{-inv} :: 'bound \Rightarrow 'st \Rightarrow bool$ **and**
 $\mu :: 'bound \Rightarrow 'st \Rightarrow nat$ **and**
 $cdcl_{NOT} :: 'st \Rightarrow 'st \Rightarrow bool$ **and**
 $cdcl_{NOT}\text{-inv} :: 'st \Rightarrow bool$ **and**
 $\mu\text{-bound} :: 'bound \Rightarrow 'st \Rightarrow nat +$

assumes

$measure\text{-}bound: \bigwedge A\ T\ V\ n. cdcl_{NOT}\text{-inv}\ T \implies bound\text{-inv}\ A\ T$
 $\implies cdcl_{NOT}\text{-restart}\ (T, n)\ (V, Suc\ n) \implies \mu\ A\ V \leq \mu\text{-bound}\ A\ T$ **and**
 $cdcl_{NOT}\text{-raw-restart}\text{-}\mu\text{-bound}$:
 $cdcl_{NOT}\text{-restart}\ (T, a)\ (V, b) \implies cdcl_{NOT}\text{-inv}\ T \implies bound\text{-inv}\ A\ T$
 $\implies \mu\text{-bound}\ A\ V \leq \mu\text{-bound}\ A\ T$

begin

lemma $rtranclp\text{-}cdcl_{NOT}\text{-raw-restart}\text{-}\mu\text{-bound}$:

$cdcl_{NOT}\text{-restart}^{**}\ (T, a)\ (V, b) \implies cdcl_{NOT}\text{-inv}\ T \implies bound\text{-inv}\ A\ T$
 $\implies \mu\text{-bound}\ A\ V \leq \mu\text{-bound}\ A\ T$
apply (*induction* *rule*: $rtranclp\text{-}induct2$)

```

apply simp
by (metis cdclNOT-raw-restart-μ-bound dual-order.trans fst-conv
      rtrancp-cdclNOT-with-restart-bound-inv rtrancp-cdclNOT-with-restart-cdclNOT-inv)

lemma cdclNOT-raw-restart-measure-bound:
  cdclNOT-restart (T, a) (V, b)  $\implies$  cdclNOT-inv T  $\implies$  bound-inv A T
   $\implies$  μ A V ≤ μ-bound A T
apply (cases rule: cdclNOT-restart.cases)
  apply simp
  using measure-bound relpowp-imp-rtrancp apply fastforce
  by (metis full-def full-unfold measure-bound2 prod.inject)

lemma rtrancp-cdclNOT-raw-restart-measure-bound:
  cdclNOT-restart** (T, a) (V, b)  $\implies$  cdclNOT-inv T  $\implies$  bound-inv A T
   $\implies$  μ A V ≤ μ-bound A T
apply (induction rule: rtrancp-induct2)
  apply (simp add: measure-bound2)
by (metis dual-order.trans fst-conv measure-bound2 r-into-rtrancp rtrancp.rtrancp-refl
      rtrancp-cdclNOT-with-restart-bound-inv rtrancp-cdclNOT-with-restart-cdclNOT-inv
      rtrancp-cdclNOT-raw-restart-μ-bound)

lemma wf-cdclNOT-restart:
  wf {(T, S). cdclNOT-restart S T ∧ cdclNOT-inv (fst S)} (is wf ?A)
proof (rule ccontr)
  assume ¬ ?thesis
  then obtain g where
    g:  $\bigwedge i. \text{cdcl}_{\text{NOT}}\text{-restart } (g\ i) (g\ (\text{Suc } i))$  and
    cdclNOT-inv-g:  $\bigwedge i. \text{cdcl}_{\text{NOT}}\text{-inv } (\text{fst } (g\ i))$ 
  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
      cdclNOT-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: unbounded (λi. f (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:  $\bigwedge T\ Ta\ m. (\text{cdcl}_{\text{NOT}} \rightsquigarrow m)\ T\ Ta \implies \text{no-step } \text{cdcl}_{\text{NOT}}\ T \implies m = 0$ 
    apply (case-tac m) by simp (meson relpowp-E2)
    have  $\exists T\ m. (\text{cdcl}_{\text{NOT}} \rightsquigarrow m)\ (\text{fst } (g\ i))\ T \wedge m \geq f\ (\text{snd } (g\ i))$ 
    using g[of i] apply (cases rule: cdclNOT-restart.cases)
    apply auto[]
    using g[of Suc i] f-ge-1 apply (cases rule: cdclNOT-restart.cases)
    apply (auto simp add: full1-def full-def dest: H dest: trancpD)
    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-rtrancp
      rtrancp-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  $?j = \mu\text{-bound}\ A\ (fst\ (g\ 1)) + 1$ 
  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:  $j \geq i \implies \text{cdcl}_{NOT}\text{-restart}^{**}\ (g\ i)\ (g\ j)$ 
      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  $\langle j > 1 \rangle$  by (simp add: cdclNOT-restart)
  have  $\mu\ A\ (fst\ (g\ j)) \leq \mu\text{-bound}\ A\ (fst\ (g\ 1))$ 
    apply (rule rtranclp-cdclNOT-raw-restart-measure-bound)
    using  $\langle \text{cdcl}_{NOT}\text{-restart}^{**}\ (fst\ (g\ 1), snd\ (g\ 1))\ (fst\ (g\ j), snd\ (g\ j)) \rangle$  apply blast
    apply (simp add: cdclNOT-inv-g)
    using  $\langle \text{bound-inv}\ A\ (fst\ (g\ 1)) \rangle$  apply simp
  done
  then have  $\mu\ A\ (fst\ (g\ j)) \leq ?j$ 
    by auto
  have inv: bound-inv A (fst (g j))
    using  $\langle \text{bound-inv}\ A\ (fst\ (g\ 1)) \rangle \langle \text{cdcl}_{NOT}\text{-inv}\ (fst\ (g\ (Suc\ 0))) \rangle$ 
     $\langle \text{cdcl}_{NOT}\text{-restart}^{**}\ (fst\ (g\ 1), snd\ (g\ 1))\ (fst\ (g\ j), snd\ (g\ j)) \rangle$ 
    rtranclp-cdclNOT-with-restart-bound-inv by auto
  obtain  $T\ m$  where
    cdclNOT-m:  $(\text{cdcl}_{NOT} \rightsquigarrow m)\ (fst\ (g\ j))\ T$  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  $\langle \mu\ A\ (fst\ (g\ j)) \leq \mu\text{-bound}\ A\ (fst\ (g\ 1)) \rangle$ 
    cdclNOT-comp-bounded[OF inv cdclNOT-inv-g, of ] cdclNOT-inv-g cdclNOT-m
     $\langle ?j < m \rangle$  by auto
qed

```

lemma *cdcl_{NOT}-restart-steps-bigger-than-bound*:

```

  assumes
    cdclNOT-restart S T and
    bound-inv A (fst S) and
    cdclNOT-inv (fst S) and
     $f\ (snd\ S) > \mu\text{-bound}\ A\ (fst\ S)$ 
  shows full1 cdclNOT (fst S) (fst T)
  using assms
  proof (induction rule: cdclNOT-restart.induct)
  case restart-full
  then show ?case by auto
next
  case (restart-step m S T n U) note st = this(1) and f = this(2) and bound-inv = this(4) and

```

$cdcl_{NOT-inv} = this(5)$ and $\mu = this(6)$
then obtain m' **where** $m: m = Suc\ m'$ **by** $(cases\ m)$ **auto**
have $\mu\ A\ S - m' = 0$
using $f\ bound-inv\ cdcl_{NOT-inv}\ \mu\ m\ rtrancpl-cdcl_{NOT-raw-restart-measure-bound}$ **by** $fastforce$
then have $False$ **using** $cdcl_{NOT-comp-n-le}[of\ m'\ S\ T\ A]$ $restart-step$ **unfolding** m **by** $simp$
then show $?case$ **by** $fast$
qed

lemma $rtrancpl-cdcl_{NOT-with-inv-inv-rtrancpl-cdcl_{NOT}}$:
assumes
 $inv: cdcl_{NOT-inv}\ S$ **and**
 $binv: bound-inv\ A\ S$
shows $(\lambda S\ T. cdcl_{NOT}\ S\ T \wedge cdcl_{NOT-inv}\ S \wedge bound-inv\ A\ S)^{**}\ S\ T \longleftrightarrow cdcl_{NOT}^{**}\ S\ T$
(is $?A^{**}\ S\ T \longleftrightarrow ?B^{**}\ S\ T)$
apply $(rule\ iffI)$
using $rtrancpl-mono[of\ ?A\ ?B]$ **apply** $blast$
apply $(induction\ rule: rtrancpl-induct)$
using $inv\ binv$ **apply** $simp$
by $(metis\ (mono-tags,\ lifting)\ binv\ inv\ rtrancpl.simps\ rtrancpl-cdcl_{NOT-bound-inv}\ rtrancpl-cdcl_{NOT-cdcl_{NOT-inv})}$

lemma $no-step-cdcl_{NOT-restart-no-step-cdcl_{NOT}}$:
assumes
 $n-s: no-step\ cdcl_{NOT-restart}\ S$ **and**
 $inv: cdcl_{NOT-inv}\ (fst\ S)$ **and**
 $binv: bound-inv\ A\ (fst\ S)$
shows $no-step\ cdcl_{NOT}\ (fst\ S)$
proof $(rule\ ccontr)$
assume $\neg\ ?thesis$
then obtain T **where** $T: cdcl_{NOT}\ (fst\ S)\ T$
by $blast$
then obtain U **where** $U: full\ (\lambda S\ T. cdcl_{NOT}\ S\ T \wedge cdcl_{NOT-inv}\ S \wedge bound-inv\ A\ S)\ T\ U$
using $wf-exists-normal-form-full[OF\ wf-cdcl_{NOT},\ of\ A\ T]$ **by** $auto$
moreover have $inv-T: cdcl_{NOT-inv}\ T$
using $\langle cdcl_{NOT}\ (fst\ S)\ T \rangle\ cdcl_{NOT-inv}\ inv$ **by** $blast$
moreover have $b-inv-T: bound-inv\ A\ T$
using $\langle cdcl_{NOT}\ (fst\ S)\ T \rangle\ binv\ bound-inv\ inv$ **by** $blast$
ultimately have $full\ cdcl_{NOT}\ T\ U$
using $rtrancpl-cdcl_{NOT-with-inv-inv-rtrancpl-cdcl_{NOT}\ rtrancpl-cdcl_{NOT-bound-inv}\ rtrancpl-cdcl_{NOT-cdcl_{NOT-inv}}$ **unfolding** $full-def$ **by** $blast$
then have $full1\ cdcl_{NOT}\ (fst\ S)\ U$
using $T\ full-fullI$ **by** $metis$
then show $False$ **by** $(metis\ n-s\ prod.collapse\ restart-full)$
qed

end

14.8 Merging backjump and learning

locale $cdcl_{NOT-merge-bj-learn-ops} =$
 $dpll-state\ trail\ clauses\ prepend-trail\ tl-trail\ add-cls_{NOT}\ remove-cls_{NOT} +$
 $decide-ops\ trail\ clauses\ prepend-trail\ tl-trail\ add-cls_{NOT}\ remove-cls_{NOT} +$
 $forget-ops\ trail\ clauses\ prepend-trail\ tl-trail\ add-cls_{NOT}\ remove-cls_{NOT}\ forget-cond +$
 $propagate-ops\ trail\ clauses\ prepend-trail\ tl-trail\ add-cls_{NOT}\ remove-cls_{NOT}\ propagate-conds$
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 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 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.simps 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  $\lambda C C' L' S.$  backjump-l-cond C 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-clsNOT remove-clsNOT:: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
propagate-conds :: ('v, unit, unit) marked-lit  $\Rightarrow$  'st  $\Rightarrow$  bool and
forget-conds :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool and
backjump-l-cond :: 'v clause  $\Rightarrow$  'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  bool +
fixes
inv :: 'st  $\Rightarrow$  bool
assumes
bj-can-jump:

```

$\bigwedge S \ C \ F' \ K \ F \ L.$
 $inv \ S$
 $\implies trail \ S = F' @ \text{Marked } K \ () \ \# \ F$
 $\implies C \in \# \ \text{clauses } S$
 $\implies trail \ S \models_{as} CNot \ C$
 $\implies undefined-lit \ F \ L$
 $\implies atm-of \ L \in atms-of-msu \ (\text{clauses } S) \cup atm-of \ ' \ (\text{lits-of } (F' @ \text{Marked } K \ () \ \# \ F))$
 $\implies clauses \ S \models_{pm} C' + \{\#L\#\}$
 $\implies F \models_{as} CNot \ C'$
 $\implies \neg no-step \ backjump-l \ S \ \text{and}$
 $cdcl_merged_inv: \bigwedge S \ T. \ cdcl_{NOT}\text{-merged-bj-learn } S \ T \implies inv \ S \implies inv \ T$
begin
abbreviation *backjump-conds* **where**
backjump-conds $\equiv \lambda-. \ C \ L \ -. \ distinct_mset \ (C + \{\#L\#\}) \wedge \neg \text{tautology} \ (C + \{\#L\#\})$
sublocale *dpll-with-backjumping-ops* *trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT}*
propagate-conds inv backjump-conds
proof (*unfold-locales, goal-cases*)
case 1
{ fix *S S'*
assume *bj: backjump-l S S' and no-dup (trail S)*
then obtain *F' K F L C' C where*
S': S' ~ prepend-trail (Propagated L ()) (reduce-trail-to_{NOT} F
(tl-trail(add-cl_{NOT} (C' + {\#L\#}) S)))
and
tr-S: trail S = F' @ Marked K () # F and
C: C ∈ # clauses S and
tr-S-C: trail S ⊨_{as} CNot C and
undef-L: undefined-lit F L and
atm-L: atm-of L ∈ atms-of-msu (clauses S) ∪ atm-of ' lits-of (trail S) and
cls-S-C': clauses S ⊨_{pm} C' + {\#L\#} and
F-C': F ⊨_{as} CNot C' and
dist: distinct-mset (C' + {\#L\#}) and
not-tauto: ¬ tautology (C' + {\#L\#})
by (*elim backjump-lE*) *simp*

have $\exists S'. \text{backjumping-ops.backjump trail clauses prepend-trail tl-trail backjump-conds } S \ S'$
apply *rule*
apply (*rule backjumping-ops.backjump.intros*)
apply *unfold-locales*
using *tr-S* **apply** *simp*
apply (*rule state-eq_{NOT}-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 *cdcl_{NOT}-merge-bj-learn-proxy2* =
cdcl_{NOT}-merge-bj-learn-proxy trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT}
propagate-conds forget-conds backjump-l-cond inv
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**
forget-conds :: 'v clause \Rightarrow 'st \Rightarrow bool **and**
backjump-l-cond :: 'v clause \Rightarrow 'v clause \Rightarrow 'v literal \Rightarrow 'st \Rightarrow bool

begin

sublocale *conflict-driven-clause-learning-ops* trail clauses prepend-trail tl-trail add-cl_{NOT}
remove-cl_{NOT} propagate-conds inv backjump-conds λC -. distinct-mset $C \wedge \neg \text{tautology } C$
forget-conds
by *unfold-locales*
end

locale *cdcl_{NOT}-merge-bj-learn* =
cdcl_{NOT}-merge-bj-learn-proxy2 trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT}
propagate-conds inv forget-conds backjump-l-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**
forget-conds :: 'v clause \Rightarrow 'st \Rightarrow bool **and**
backjump-l-cond :: 'v clause \Rightarrow 'v clause \Rightarrow 'v literal \Rightarrow 'st \Rightarrow bool +
assumes
dpll-bj-inv: $\bigwedge S T. \text{dpll-bj } S T \Longrightarrow \text{inv } S \Longrightarrow \text{inv } T$ **and**
learn-inv: $\bigwedge S T. \text{learn } S T \Longrightarrow \text{inv } S \Longrightarrow \text{inv } T$
begin

interpretation *cdcl_{NOT}*:
conflict-driven-clause-learning trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT}
propagate-conds inv backjump-conds λC -. distinct-mset $C \wedge \neg \text{tautology } C$ forget-conds
apply *unfold-locales*
apply (*simp only*: *cdcl_{NOT}.simps*)
using *cdcl_{NOT}-merged-bj-learn-forget_{NOT} cdcl-merged-inv learn-inv*
by (*auto simp add: cdcl_{NOT}.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 $\exists C' L. \text{learn } S (\text{add-cl}_{\text{NOT}} (C' + \{\#L\# \}) S)$
 $\wedge \text{backjump} (\text{add-cl}_{\text{NOT}} (C' + \{\#L\# \}) S) T$
 $\wedge \text{atms-of } (C' + \{\#L\# \}) \subseteq \text{atms-of-msu } (\text{clauses } S) \cup \text{atm-of } ' (\text{lits-of } (\text{trail } S))$
proof –
obtain $C F' K F L l C'$ **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**
 $C-cl_{-}S$: $C \in \# clauses\ S$ **and**
 $tr-S-CNot-C$: $trail\ S \models_{as}\ CNot\ C$ **and**
 $undef$: $undefined-lit\ F\ L$ **and**
 $atm-L$: $atm-of\ L \in atms-of-msu\ (clauses\ S) \cup atm-of\ ' (lits-of\ (trail\ S))$ **and**
 $clss-C$: $clauses\ S \models_{pm}\ C' + \{\#L\#\}$ **and**
 $F \models_{as}\ CNot\ C'$ **and**
 $distinct$: $distinct-mset\ (C' + \{\#L\#\})$ **and**
 $not-tauto$: $\neg tautology\ (C' + \{\#L\#\})$
using $bt\ inv$ **by** $(elim\ backjump-lE)\ simp$
have $atms-C'$: $atms-of\ C' \subseteq atm-of\ ' (lits-of\ F)$
proof –
obtain $ll :: 'v \Rightarrow ('v\ literal \Rightarrow 'v) \Rightarrow 'v\ literal\ set \Rightarrow 'v\ literal$ **where**
 $\forall v\ f\ L. v \notin f\ 'L \vee v = f\ (ll\ v\ f\ L) \wedge ll\ v\ f\ L \in L$
by $moura$
then show $?thesis$ **unfolding** $tr-S$
by $(metis\ (no-types)\ \langle F \models_{as}\ CNot\ C' \rangle\ atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set\ atm-of-def\ in-CNot-implies-uminus(2)\ mem-set-mset-iff\ subsetI)$
qed
then have $atms-of\ (C' + \{\#L\#\}) \subseteq atms-of-msu\ (clauses\ S) \cup atm-of\ ' (lits-of\ (trail\ S))$
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 $\langle F \models_{as}\ CNot\ C' \rangle\ C-cl_{-}S\ tr-S-CNot-C\ undef\ T\ distinct\ not-tauto\ n-d$
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 $S\ T \implies inv\ S \implies no-dup\ (trail\ S) \implies cdcl_{NOT}^{++}\ S\ T$
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 ($add-cl_{NOT} (C' + \{\#L\# \}) S$) \wedge
backjump ($add-cl_{NOT} (C' + \{\#L\# \}) S$) $T \wedge$
 $atms-of (C' + \{\#L\# \}) \subseteq atms-of-msu (clauses S) \cup atm-of ' lits-of (trail S)$
using $n-d$ backjump-l-learn-backjump[OF bt inv] **by** blast
then have $f4$: $cdcl_{NOT} S (add-cl_{NOT} (C' + \{\#L\# \}) S)$
using $n-d$ c-learn **by** blast
have $cdcl_{NOT} (add-cl_{NOT} (C' + \{\#L\# \}) S) T$
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 μ_{CDCL}' -merged $:: 'v$ literal multiset set $\Rightarrow 'st \Rightarrow nat$ **where**

μ_{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 $\mu_{CDCL}'\text{-merged } A \ T < \mu_{CDCL}'\text{-merged } A \ S$
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**
 $(2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } T)$
 $< (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } S)$
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 $\mu_{CDCL}'\text{-merged-def } \mu_C'\text{-def}$ **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**
 $(2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } T)$
 $< (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } S)$
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 $\mu_{CDCL}'\text{-merged-def } \mu_C'\text{-def}$ **by** *simp*
next
case (*cdcl*_{NOT}-merged-bj-learn-forget_{NOT} *T*)
have *card* (*set-mset* (*clauses* *T*)) < *card* (*set-mset* (*clauses* *S*))
using (*forget*_{NOT} *S T*) **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 (*forget*_{NOT} *S T*) **by** (*auto elim: forgetE*)
then have
 $(2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } T)$
 $= (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } S)$
by *auto*
ultimately show ?*case*
unfolding $\mu_{CDCL}'\text{-merged-def } \mu_C'\text{-def}$ **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-cls*_{NOT} (*C' + \{\#L\#*}) *S*) **and**
bj: backjump (*add-cls*_{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*: $\text{card}(\text{set-mset}(\text{clauses } T)) \leq 1 + \text{card}(\text{set-mset}(\text{clauses } S))$
using *bj-l inv* **by** (*force elim!*: *backjump-lE simp*: *card-insert-if*)
have
 $((2 + \text{card}(\text{atms-of-ms } A)) \wedge (1 + \text{card}(\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card}(\text{atms-of-ms } A)) (2 + \text{card}(\text{atms-of-ms } A)) (\text{trail-weight } T))$
 $< ((2 + \text{card}(\text{atms-of-ms } A)) \wedge (1 + \text{card}(\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card}(\text{atms-of-ms } A)) (2 + \text{card}(\text{atms-of-ms } A))$
 $(\text{trail-weight}(\text{add-cl}_{NOT}(C' + \{\#L\# \}) S)))$
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 $((2 + \text{card}(\text{atms-of-ms } A)) \wedge (1 + \text{card}(\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card}(\text{atms-of-ms } A)) (2 + \text{card}(\text{atms-of-ms } A)) (\text{trail-weight } T))$
 $< ((2 + \text{card}(\text{atms-of-ms } A)) \wedge (1 + \text{card}(\text{atms-of-ms } A))$
 $- \mu_C (1 + \text{card}(\text{atms-of-ms } A)) (2 + \text{card}(\text{atms-of-ms } A)) (\text{trail-weight } S))$
using *n-d* **by** *auto*
then show *?case*
using *card-T-S* **unfolding** $\mu_{CDCL}'\text{-merged-def}$ $\mu_C'\text{-def}$ **by** *linarith*
qed

lemma *wf-cdcl_{NOT}-merged-bj-learn*:
assumes
fin-A: *finite A*
shows *wf* $\{(T, S).$
 $(\text{inv } S \wedge \text{atms-of-msu}(\text{clauses } S) \subseteq \text{atms-of-ms } A \wedge \text{atm-of ' lits-of}(\text{trail } S) \subseteq \text{atms-of-ms } A$
 $\wedge \text{no-dup}(\text{trail } S))$
 $\wedge \text{cdcl}_{NOT}\text{-merged-bj-learn } S T\}$
apply (*rule wfP-if-measure[of - - $\mu_{CDCL}'\text{-merged } A$]*)
using *cdcl_{NOT}-decreasing-measure' fin-A* **by** *simp*

lemma *tranclp-cdcl_{NOT}-cdcl_{NOT}-tranclp*:
assumes
 $\text{cdcl}_{NOT}\text{-merged-bj-learn}^{++} S T$ **and**
inv: *inv S* **and**
atm-clss: $\text{atms-of-msu}(\text{clauses } S) \subseteq \text{atms-of-ms } A$ **and**
atm-trail: $\text{atm-of ' lits-of}(\text{trail } S) \subseteq \text{atms-of-ms } A$ **and**
n-d: *no-dup (trail S)* **and**
fin-A[simp]: *finite A*
shows $(T, S) \in \{(T, S).$
 $(\text{inv } S \wedge \text{atms-of-msu}(\text{clauses } S) \subseteq \text{atms-of-ms } A \wedge \text{atm-of ' lits-of}(\text{trail } S) \subseteq \text{atms-of-ms } A$
 $\wedge \text{no-dup}(\text{trail } S))$
 $\wedge \text{cdcl}_{NOT}\text{-merged-bj-learn } S T\}^+ (\text{is } - \in ?P^+)$
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** *cdcl_{NOT} = this(2)* **and** *IH = this(3)*
have *cdcl_{NOT}** S T*
apply (*rule rtranclp-cdcl_{NOT}-merged-bj-learn-is-rtranclp-cdcl_{NOT}*)

```

    using st cdclNOT inv n-d atm-clss atm-trail inv by auto
have inv T
    apply (rule rtrancpl-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)  $\subseteq$  atms-of-ms A
    using cdclNOT.rtrancpl-cdclNOT-trail-clauses-bound[OF  $\langle \text{cdcl}_{\text{NOT}}^{**} S T \rangle$  inv n-d atm-clss atm-trail]
    by fast
moreover have atm-of ' (lits-of (trail T))  $\subseteq$  atms-of-ms A
    using cdclNOT.rtrancpl-cdclNOT-trail-clauses-bound[OF  $\langle \text{cdcl}_{\text{NOT}}^{**} S T \rangle$  inv n-d atm-clss atm-trail]
    by fast
moreover have no-dup (trail T)
    using cdclNOT.rtrancpl-cdclNOT-no-dup[OF  $\langle \text{cdcl}_{\text{NOT}}^{**} S T \rangle$  inv n-d] by fast
ultimately have (U, T)  $\in$  ?P
    using cdclNOT by auto
then show ?case using IH by (simp add: trancpl-into-trancpl2)
qed

```

```

lemma wf-trancpl-cdclNOT-merged-bj-learn:
  assumes 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))
     $\wedge$  cdclNOT-merged-bj-learn++ S T}
  apply (rule wf-subset)
  apply (rule wf-trancpl[OF wf-cdclNOT-merged-bj-learn])
  using assms apply simp
using trancpl-cdclNOT-cdclNOT-trancpl[OF - - - -  $\langle \text{finite } A \rangle$ ] 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)  $\subseteq$  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 S  $\models_{\text{asm}}$  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  $\models_{\text{as}}$  ?N
  | (sat') satisfiable ?N and  $\neg$  ?M  $\models_{\text{as}}$  ?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 ∈ ?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 $?I = I \cup \{P \mid P. P \in \text{lits-of } ?M \wedge \text{atm-of } P \notin \text{atm-of ' } I\}$

let $?O = \{\{\# \text{lit-of } L\# \mid L. \text{is-marked } L \wedge L \in \text{set } ?M \wedge \text{atm-of } (\text{lit-of } L) \notin \text{atms-of-ms } ?N\}$

have *cons-I'*: *consistent-interp* $?I$

using *cons* **using** $\langle \text{no-dup } ?M \rangle$ **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* $?I$ $(?N \cup \text{unmark } ?M)$

using *tot* *atms-of-s-def* **unfolding** *total-over-m-def* *total-over-set-def*

by *fastforce*

have $\{P \mid P. P \in \text{lits-of } ?M \wedge \text{atm-of } P \notin \text{atm-of ' } I\} \models_s ?O$

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* $?N \subseteq \text{atm-of ' } \text{lits-of } ?M$

proof (*rule ccontr*)

assume $\neg ?thesis$

then obtain *l* :: '*v* **where**

l-N: *l* $\in \text{atms-of-ms } ?N$ **and**

l-M: *l* $\notin \text{atm-of ' } \text{lits-of } ?M$

by *auto*

have *undefined-lit* $?M$ $(\text{Pos } l)$

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 *decide_{NOT}* *S* $(\text{prepend-trail } (\text{Marked } (\text{Pos } l) ()) S)$

by (*metis undefined-lit ?M (Pos l) decide_{NOT}.intros l-N literal.sel(1)*
state-eq_{NOT}-ref)

then show *False*

using *cdcl_{NOT}-merged-bj-learn-decide_{NOT} 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*)

have $\exists l \in \text{set } ?M. \text{is-marked } l$

proof (*rule ccontr*)

let $?O = \{\{\# \text{lit-of } L\# \mid L. \text{is-marked } L \wedge L \in \text{set } ?M \wedge \text{atm-of } (\text{lit-of } L) \notin \text{atms-of-ms } ?N\}$

have $\vartheta[\text{iff}]: \bigwedge I. \text{total-over-m } I$ $(?N \cup ?O \cup \text{unmark } ?M)$

$\longleftrightarrow \text{total-over-m } I$ $(?N \cup \text{unmark } ?M)$

unfolding *total-over-set-def* *total-over-m-def* *atms-of-ms-def* **by** *auto*

assume $\neg ?thesis$

then have $[\text{simp}]: \{\{\# \text{lit-of } L\# \mid L. \text{is-marked } L \wedge L \in \text{set } ?M\}$

```

= { {#lit-of L#} | L. is-marked L ∧ L ∈ set ?M ∧ atm-of (lit-of L) ∉ atms-of-ms ?N }
by auto
then have ?N ∪ ?O ⊨ps unmark ?M
using all-decomposition-implies-propagated-lits-are-implied[OF decomp] by auto

then have ?I ⊨s unmark ?M
using cons-I' I'-N tot-I' ⟨?I ⊨s ?N ∪ ?O⟩ unfolding ∅ true-clss-clss-def by blast
then have lits-of ?M ⊆ ?I
unfolding true-clss-def lits-of-def by auto
then have ?M ⊨as ?N
using I'-N ⟨C ∈ ?N⟩ ⟨¬ ?M ⊨a C⟩ cons-I' atms-N-M
by (meson ⟨trail S ⊨as CNot C⟩ consistent-CNot-not rev-subsetD sup-ge1 true-annot-def
true-annot-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 d :: unit and
F F' :: ('v, unit, unit) marked-lit list where
M-K: ?M = F' @ Marked K () # F and
nm: ∀ f ∈ set F'. ¬ 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 ∈ set ?M
unfolding M-K by auto
let ?C = image-mset lit-of {#L ∈ #mset ?M. is-marked L ∧ L ≠ ?K#} :: 'v literal multiset
let ?C' = set-mset (image-mset (λL::'v literal. {#L#}) (?C + {#lit-of ?K#}))
have ?N ∪ { {#lit-of L#} | L. is-marked L ∧ L ∈ set ?M } ⊨ps unmark ?M
using all-decomposition-implies-propagated-lits-are-implied[OF decomp] .
moreover have C': ?C' = { {#lit-of L#} | L. is-marked L ∧ L ∈ set ?M }
unfolding M-K apply standard
apply force
using IntI by auto
ultimately have N-C-M: ?N ∪ ?C' ⊨ps unmark ?M
by auto
have N-M-False: ?N ∪ (λL. {#lit-of L#}) ' (set ?M) ⊨ps { {#} }
using M ⟨?M ⊨as CNot C⟩ ⟨C ∈ ?N⟩ unfolding true-clss-clss-def true-annot-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 ⟨no-dup ?M⟩ unfolding M-K by (simp add: defined-lit-map)
moreover
have ?N ∪ ?C' ⊨ps { {#} }
proof -
have A: ?N ∪ ?C' ∪ unmark ?M =
?N ∪ unmark ?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 ⊨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 ∪ { image-mset uminus ?C + {#-K#} })) and
cons: consistent-interp I and

```

```

  I  $\models_s$  ?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 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)) =  $\neg$  Pos (atm-of (lit-of x))
      by simp
    ultimately have  $\neg$  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))
  } 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-cl-def Bex-mset-def
    using  $\langle (K \in I \wedge \neg K \notin I) \vee (\neg K \in I \wedge K \notin I) \rangle$ 
    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  $\neg$ 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  $\neg$ 
    have st: cdclNOT-merged-bj-learn** S T and n-s: no-step cdclNOT-merged-bj-learn T

```

```

    using full unfolding full-def by blast+
  then have st:  $cdcl_{NOT}^{**} S T$ 
    using inv rtrancpl-cdclNOT-merged-bj-learn-is-rtrancpl-cdclNOT-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 cdclNOT.rtrancpl-cdclNOT-trail-clauses-bound[OF st inv n-d atms- $S$  atms-trail] by blast+
  moreover have no-dup (trail  $T$ )
    using cdclNOT.rtrancpl-cdclNOT-no-dup inv n-d st by blast
  moreover have inv  $T$ 
    using cdclNOT.rtrancpl-cdclNOT-inv inv st by blast
  moreover have all-decomposition-implies-m (clauses  $T$ ) (get-all-marked-decomposition (trail  $T$ ))
    using cdclNOT.rtrancpl-cdclNOT-all-decomposition-implies inv st decomp n-d by blast
  ultimately show ?thesis
    using cdclNOT-merged-bj-learn-final-state[of  $T A$ ] ⟨finite  $A$ ⟩ n-s by fast
qed
end

```

14.8.1 Instantiations

```

locale cdclNOT-with-backtrack-and-restarts =
  conflict-driven-clause-learning-learning-before-backjump-only-distinct-learnt trail clauses
  prepend-trail tl-trail add-clNOT remove-clNOT propagate-conds inv backjump-conds
  learn-restrictions forget-restrictions
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 clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool and
  learn-restrictions forget-restrictions :: 'v 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:  $\bigwedge S T. inv S \Rightarrow T \sim \text{reduce-trail-to}_{NOT} ([::'a \text{ list}) S \Rightarrow inv T$ 
begin

```

lemma bound-inv-inv:

```

assumes
  inv  $S$  and
  n-d: no-dup (trail  $S$ ) and
  atms-clss- $S$ - $A$ : 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
  cdclNOT: cdclNOT  $S T$ 
shows
  atms-of-msu (clauses  $T$ )  $\subseteq$  atms-of-ms  $A$  and
  atm-of ' lits-of (trail  $T$ )  $\subseteq$  atms-of-ms  $A$  and
  finite  $A$ 
proof –
  have cdclNOT  $S T$ 
    using ⟨inv  $S$ ⟩ cdclNOT by linarith
  then have atms-of-msu (clauses  $T$ )  $\subseteq$  atms-of-msu (clauses  $S$ )  $\cup$  atm-of ' lits-of (trail  $S$ )

```

```

using  $\langle \text{inv } S \rangle$ 
by (meson conflict-driven-clause-learning-ops.cdclNOT-atms-of-ms-clauses-decreasing
    conflict-driven-clause-learning-ops-axioms n-d)
then show atms-of-msu (clauses T)  $\subseteq$  atms-of-ms A
    using atms-clss-S-A atms-trail-S-A by blast
next
show atm-of ' lits-of (trail T)  $\subseteq$  atms-of-ms A
    by (meson  $\langle \text{inv } S \rangle$  atms-clss-S-A atms-trail-S-A cdclNOT cdclNOT-atms-in-trail-in-set n-d)
next
show finite A
    using  $\langle \text{finite A} \rangle$  by simp
qed

sublocale cdclNOT-increasing-restarts-ops  $\lambda S T. T \sim \text{reduce-trail-to}_{NOT} ([::'a \text{ list}) S cdcl_{NOT} f$ 
     $\lambda A S. \text{atms-of-msu (clauses S)} \subseteq \text{atms-of-ms A} \wedge \text{atm-of ' lits-of (trail S)} \subseteq \text{atms-of-ms A} \wedge$ 
    finite A
     $\mu_{CDCL}' \lambda S. \text{inv S} \wedge \text{no-dup (trail S)}$ 
     $\mu_{CDCL}'\text{-bound}$ 
apply unfold-locales
    apply (simp add: unbounded)
    using f-ge-1 apply force
    using bound-inv-inv apply meson
    apply (rule cdclNOT-decreasing-measure'; simp)
    apply (rule rtranclp-cdclNOT- $\mu_{CDCL}'\text{-bound}$ ; simp)
    apply (rule rtranclp- $\mu_{CDCL}'\text{-bound-decreasing}$ ; simp)
    apply auto[]
    apply auto[]
    using cdclNOT-inv cdclNOT-no-dup apply blast
using inv-restart apply auto[]
done

```

abbreviation *cdcl_{NOT}-l* **where**

```

cdclNOT-l  $\equiv$ 
    conflict-driven-clause-learning-ops.cdclNOT trail clauses prepend-trail tl-trail add-clNOT
    remove-clNOT propagate-conds ( $\lambda - - S T. \text{backjump S T}$ )
    ( $\lambda C S. \text{distinct-mset } C \wedge \neg \text{tautology } C \wedge \text{learn-restrictions } C S$ 
         $\wedge (\exists F K F' C' L. \text{trail } S = F' @ \text{Marked } K () \# F \wedge C = C' + \{\#L\}$ 
             $\wedge F \models_{as} CNot C' \wedge C' + \{\#L\} \notin \# \text{clauses } S))$ 
    ( $\lambda C S. \neg (\exists F' F K L. \text{trail } S = F' @ \text{Marked } K () \# F \wedge F \models_{as} CNot (C - \{\#L\}))$ 
         $\wedge \text{forget-restrictions } C S)$ 

```

lemma *cdcl_{NOT}-with-restart- $\mu_{CDCL}'\text{-le-}\mu_{CDCL}'\text{-bound}$:*

```

assumes
    cdclNOT: cdclNOT-restart (T, a) (V, b) and
    cdclNOT-inv:
        inv T
        no-dup (trail T) and
    bound-inv:
        atms-of-msu (clauses T)  $\subseteq$  atms-of-ms A
        atm-of ' lits-of (trail T)  $\subseteq$  atms-of-ms A
        finite A
shows  $\mu_{CDCL}' A V \leq \mu_{CDCL}'\text{-bound A T}$ 
using cdclNOT-inv bound-inv
proof (induction rule: cdclNOT-with-restart-induct[OF cdclNOT])
    case (1 m S T n U) note U = this(3)

```

```

show ?case
  apply (rule rtrancpl-cdclNOT-μCDCL'-bound-reduce-trail-toNOT[of S T])
    using ⟨(cdclNOT  $\widetilde{\sim}$  m) S T⟩ 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-cdclNOT-μCDCL'-bound)
    using full 2 unfolding full1-def by force+
qed

lemma cdclNOT-with-restart-μCDCL'-bound-le-μCDCL'-bound:
  assumes
    cdclNOT: cdclNOT-restart (T, a) (V, b) and
    cdclNOT-inv:
      inv T
      no-dup (trail T) and
    bound-inv:
      atms-of-msu (clauses T) ⊆ atms-of-ms A
      atm-of ' lits-of (trail T) ⊆ atms-of-ms A
      finite A
  shows μCDCL'-bound A V ≤ μCDCL'-bound A T
  using cdclNOT-inv bound-inv
proof (induction rule: cdclNOT-with-restart-induct[OF cdclNOT])
  case (1 m S T n U) note U = this(3)
  have μCDCL'-bound A T ≤ μCDCL'-bound A S
    apply (rule rtrancpl-μCDCL'-bound-decreasing)
    using ⟨(cdclNOT  $\widetilde{\sim}$  m) S T⟩ apply (fastforce dest!: relpowp-imp-rtrancpl)
    using 1 by auto
  then show ?case using U unfolding μCDCL'-bound-def by auto
next
  case (2 S T n) note full = this(2)
  show ?case
    apply (rule rtrancpl-μCDCL'-bound-decreasing)
    using full 2 unfolding full1-def by force+
qed

sublocale cdclNOT-increasing-restarts - - - - f
  λS T. T ~ reduce-trail-toNOT ([::'a list) S
  λA S. atms-of-msu (clauses S) ⊆ atms-of-ms A
    ∧ atm-of ' lits-of (trail S) ⊆ atms-of-ms A ∧ finite A
  μCDCL' cdclNOT
  λS. inv S ∧ no-dup (trail S)
  μCDCL'-bound
apply unfold-locales
  using cdclNOT-with-restart-μCDCL'-le-μCDCL'-bound apply simp
  using cdclNOT-with-restart-μCDCL'-bound-le-μCDCL'-bound apply simp
done

lemma cdclNOT-restart-all-decomposition-implies:
  assumes cdclNOT-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 rtrancp-cdclNOT-all-decomposition-implies by (auto dest!: trancp-into-rtrancp
    simp: full1-def)

lemma rtrancp-cdclNOT-restart-all-decomposition-implies:
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(1)
proof (induction rule: rtrancp-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 rtrancp-cdclNOT-with-restart-cdclNOT-inv[OF st] inv n-d by blast
moreover have no-dup (trail (fst T))
    using rtrancp-cdclNOT-with-restart-cdclNOT-inv[OF st] inv n-d by blast
ultimately show ?case
    using cdclNOT-restart-all-decomposition-implies r IH n-d by fast
qed

lemma cdclNOT-restart-sat-ext-iff:
assumes
    st: cdclNOT-restart S T and
    n-d: no-dup (trail (fst S)) and
    inv: 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)
case (restart-step m S T n U)
then show ?case
    using rtrancp-cdclNOT-bj-sat-ext-iff n-d by (fastforce dest!: relpowp-imp-rtrancp)
next
case restart-full
then show ?case using rtrancp-cdclNOT-bj-sat-ext-iff unfolding full1-def
by (fastforce dest!: trancp-into-rtrancp)
qed

lemma rtrancp-cdclNOT-restart-sat-ext-iff:
assumes
    st: cdclNOT-restart** S T and
    n-d: no-dup (trail (fst S)) and
    inv: inv (fst S)
shows  $I \models_{\text{sextm}} \text{clauses (fst S)} \longleftrightarrow I \models_{\text{sextm}} \text{clauses (fst T)}$ 
using st
proof (induction)
case base
then show ?case by simp
next

```

case (*step* T U) **note** $st = \text{this}(1)$ **and** $r = \text{this}(2)$ **and** $IH = \text{this}(3)$
have inv (*fst* T)
 using $rtrancp\text{-}cdcl_{NOT}\text{-with-restart-cdcl}_{NOT}\text{-inv}[OF\ st]\ inv\ n\text{-}d$ **by** *blast*+
moreover **have** *no-dup* (*trail* (*fst* T))
 using $rtrancp\text{-}cdcl_{NOT}\text{-with-restart-cdcl}_{NOT}\text{-inv}\ rtrancp\text{-}cdcl_{NOT}\text{-no-dup}\ st\ inv\ n\text{-}d$ **by** *blast*
ultimately **show** *?case*
 using $cdcl_{NOT}\text{-restart-sat-ext-iff}[OF\ r]\ IH$ **by** *blast*
qed

theorem *full-cdcl_{NOT}-restart-backjump-final-state:*

fixes $A :: 'v\ literal\ multiset\ set$ **and** $S\ T :: 'st$

assumes

full: $full\ cdcl_{NOT}\text{-restart}\ (S, n)\ (T, m)$ **and**

atms-S: $atms\text{-of}\text{-}msu\ (clauses\ S) \subseteq atms\text{-of}\text{-}ms\ A$ **and**

atms-trail: $atm\text{-of}\ 'lits\text{-of}\ (trail\ S) \subseteq atms\text{-of}\text{-}ms\ A$ **and**

n-d: *no-dup* (*trail* S) **and**

fin-A[simp]: *finite* A **and**

inv: $inv\ S$ **and**

decomp: $all\text{-decomposition}\text{-implies}\text{-}m\ (clauses\ S)\ (get\text{-all}\text{-marked}\text{-decomposition}\ (trail\ S))$

shows $unsatisfiable\ (set\text{-mset}\ (clauses\ S))$

$\vee (lits\text{-of}\ (trail\ T) \models_{sextm}\ clauses\ S \wedge satisfiable\ (set\text{-mset}\ (clauses\ S)))$

proof –

have st : $cdcl_{NOT}\text{-restart}^{**}\ (S, n)\ (T, m)$ **and**

n-s: $no\text{-step}\ cdcl_{NOT}\text{-restart}\ (T, m)$

using *full* **unfolding** *full-def* **by** *fast*+

have $binv\text{-}T$: $atms\text{-of}\text{-}msu\ (clauses\ T) \subseteq atms\text{-of}\text{-}ms\ A$ $atm\text{-of}\ 'lits\text{-of}\ (trail\ T) \subseteq atms\text{-of}\text{-}ms\ A$

using $rtrancp\text{-}cdcl_{NOT}\text{-with-restart-bound-inv}[OF\ st, of\ A]\ inv\ n\text{-}d\ atms\text{-}S\ atms\text{-}trail$

by *auto*

moreover **have** $inv\text{-}T$: *no-dup* (*trail* T) $inv\ T$

using $rtrancp\text{-}cdcl_{NOT}\text{-with-restart-cdcl}_{NOT}\text{-inv}[OF\ st]\ inv\ n\text{-}d$ **by** *auto*

moreover **have** $all\text{-decomposition}\text{-implies}\text{-}m\ (clauses\ T)\ (get\text{-all}\text{-marked}\text{-decomposition}\ (trail\ T))$

using $rtrancp\text{-}cdcl_{NOT}\text{-restart-all-decomposition}\text{-implies}[OF\ st]\ inv\ n\text{-}d$

decomp **by** *auto*

ultimately **have** T : $unsatisfiable\ (set\text{-mset}\ (clauses\ T))$

$\vee (trail\ T \models_{asm}\ clauses\ T \wedge satisfiable\ (set\text{-mset}\ (clauses\ T)))$

using $no\text{-step}\text{-}cdcl_{NOT}\text{-restart}\text{-}no\text{-step}\text{-}cdcl_{NOT}[of\ (T, m)\ A]\ n\text{-}s$

$cdcl_{NOT}\text{-final-state}[of\ T\ A]$ **unfolding** $cdcl_{NOT}\text{-NOT-all-inv-def}$ **by** *auto*

have $eq\text{-sat}\text{-}S\text{-}T$: $\bigwedge I. I \models_{sextm}\ clauses\ S \longleftrightarrow I \models_{sextm}\ clauses\ T$

using $rtrancp\text{-}cdcl_{NOT}\text{-restart-sat-ext-iff}[OF\ st]\ inv\ n\text{-}d\ atms\text{-}S$

atms-trail **by** *auto*

have $cons\text{-}T$: $consistent\text{-interp}\ (lits\text{-of}\ (trail\ T))$

using $inv\text{-}T(1)\ distinctconsistent\text{-interp}$ **by** *blast*

consider

$(unsat)\ unsatisfiable\ (set\text{-mset}\ (clauses\ T))$

$| (sat)\ trail\ T \models_{asm}\ clauses\ T$ **and** $satisfiable\ (set\text{-mset}\ (clauses\ T))$

using T **by** *blast*

then **show** *?thesis*

proof *cases*

case *unsat*

then **have** $unsatisfiable\ (set\text{-mset}\ (clauses\ S))$

using $eq\text{-sat}\text{-}S\text{-}T\ consistent\text{-true-clss-ext-satisfiable}\ true\text{-clss-imp-true-clss-ext}$

unfolding $satisfiable\text{-def}$ **by** *blast*

then **show** *?thesis* **by** *fast*

next

case *sat*


```

then have lits-of (trail T)  $\models_{\text{sextm}}$  clauses S
  using rtrancp-cdclNOT-restart-sat-ext-iff[OF st] inv n-d atms-S
    atms-trail by (auto simp: true-clss-imp-true-cls-ext true-annots-true-cls)
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-clsNOT remove-clsNOT +
propagate-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT propagate-conds +
backjumping-ops trail clauses prepend-trail tl-trail add-clsNOT remove-clsNOT λ- - - -. 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-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
begin
lemma backjump-bj-can-jump:
assumes
  tr-S: trail S = F' @ Marked K () # F and
  C: C ∈ # 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 ∈ atms-of-msu (clauses S) ∪ 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 ¬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 λ- - - -. 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-clsNOT remove-clsNOT
propagate-conds inv forget-conds
  λC C' L' S. distinct-mset (C' + {#L#}) ∧ backjump-l-cond C C' L' S
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

```

forget-conds :: 'v clause \Rightarrow 'st \Rightarrow bool **and**
backjump-l-cond :: 'v clause \Rightarrow '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: $\bigwedge S\ T. \text{inv } S \Rightarrow T \sim \text{reduce-trail-to}_{NOT} \ \square \ S \Rightarrow \text{inv } T$
begin

interpretation *cdcl_{NOT}*:

conflict-driven-clause-learning-ops trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT}
propagate-conds inv backjump-conds ($\lambda C \neg. \text{distinct-mset } C \wedge \neg \text{tautology } C$) *forget-conds*
by *unfold-locale*

interpretation *cdcl_{NOT}*:

conflict-driven-clause-learning trail clauses prepend-trail tl-trail add-cl_{NOT} remove-cl_{NOT}
propagate-conds inv backjump-conds ($\lambda C \neg. \text{distinct-mset } C \wedge \neg \text{tautology } C$) *forget-conds*
apply *unfold-locale*
using *cdcl_{NOT}-merged-bj-learn-forget_{NOT}* *cdcl-merged-inv* *learn-inv*
by (*auto simp add: cdcl_{NOT}.simps dpll-bj-inv*)

definition *not-simplified-cl* $A = \{\#C \in \# A. \text{tautology } C \vee \neg \text{distinct-mset } C\}$

lemma *simple-clss-or-not-simplified-cl*:

assumes *atms-of-msu* (*clauses S*) \subseteq *atms-of-ms A* **and**
 $x \in \# \text{clauses } S$ **and** *finite A*
shows $x \in \text{simple-clss } (\text{atms-of-ms } A) \vee x \in \# \text{not-simplified-cl } (\text{clauses } S)$

proof –

consider

(*simpl*) $\neg \text{tautology } x$ **and** *distinct-mset x*
 | (*n-simp*) $\text{tautology } x \vee \neg \text{distinct-mset } x$
by *auto*

then show *?thesis*

proof *cases*

case *simpl*

then have $x \in \text{simple-clss } (\text{atms-of-ms } A)$

by (*meson* *assms* *atms-of-atms-of-ms-mono* *atms-of-ms-finite* *simple-clss-mono*
distinct-mset-not-tautology-implies-in-simple-clss *finite-subset*
mem-set-mset-iff subsetCE)

then show *?thesis* **by** *blast*

next

case *n-simp*

then have $x \in \# \text{not-simplified-cl } (\text{clauses } S)$

using ($x \in \# \text{clauses } S$) **unfolding** *not-simplified-cl-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**

$atms\text{-}trail: atm\text{-}of \text{ ' (lits-of (trail } S)) \subseteq atms\text{-}of\text{-}ms \ A$ **and**
 $n\text{-}d: no\text{-}dup \ (trail \ S)$ **and**
 $fin\text{-}A[simp]: finite \ A$
shows $set\text{-}mset \ (clauses \ T) \subseteq set\text{-}mset \ (not\text{-}simplified\text{-}cls \ (clauses \ S))$
 $\cup \ simple\text{-}clss \ (atms\text{-}of\text{-}ms \ A)$
using $assms$
proof ($induction \ rule: cdcl_{NOT}\text{-}merged\text{-}bj\text{-}learn.induct$)
case $cdcl_{NOT}\text{-}merged\text{-}bj\text{-}learn\text{-}decide_{NOT}$
then show $?case \ using \ dpll\text{-}bj\text{-}clauses \ by \ (force \ dest!: \ simple\text{-}clss\text{-}or\text{-}not\text{-}simplified\text{-}cls)$
next
case $cdcl_{NOT}\text{-}merged\text{-}bj\text{-}learn\text{-}propagate_{NOT}$
then show $?case \ using \ dpll\text{-}bj\text{-}clauses \ by \ (force \ dest!: \ simple\text{-}clss\text{-}or\text{-}not\text{-}simplified\text{-}cls)$
next
case $cdcl_{NOT}\text{-}merged\text{-}bj\text{-}learn\text{-}forget_{NOT}$
then show $?case \ using \ clauses\text{-}remove\text{-}cls_{NOT} \ unfolding \ state\text{-}eq_{NOT}\text{-}def$
 $by \ (force \ elim!: \ forgetE \ dest: \ simple\text{-}clss\text{-}or\text{-}not\text{-}simplified\text{-}cls)$
next
case ($cdcl_{NOT}\text{-}merged\text{-}bj\text{-}learn\text{-}backjump\text{-}l \ T$) **note** $bj = this(1)$ **and** $inv = this(2)$ **and**
 $atms\text{-}clss = this(3)$ **and** $atms\text{-}trail = this(4)$ **and** $n\text{-}d = this(5)$

have $cdcl_{NOT}^{**} \ S \ T$
apply ($rule \ rtranclp\text{-}cdcl_{NOT}\text{-}merged\text{-}bj\text{-}learn\text{-}is\text{-}rtranclp\text{-}cdcl_{NOT}$)
using $\langle backjump\text{-}l \ S \ T \rangle \ inv \ cdcl_{NOT}\text{-}merged\text{-}bj\text{-}learn.simps \ n\text{-}d \ by \ blast+$
have $atm\text{-}of \text{ ' (lits-of (trail } T)) \subseteq atms\text{-}of\text{-}ms \ A$
using $cdcl_{NOT}.rtranclp\text{-}cdcl_{NOT}\text{-}trail\text{-}clauses\text{-}bound[OF \ \langle cdcl_{NOT}^{**} \ S \ T \rangle \ inv \ atms\text{-}trail \ atms\text{-}clss$
 $n\text{-}d \ by \ auto$
have $atms\text{-}of\text{-}msu \ (clauses \ T) \subseteq atms\text{-}of\text{-}ms \ A$
using $cdcl_{NOT}.rtranclp\text{-}cdcl_{NOT}\text{-}trail\text{-}clauses\text{-}bound[OF \ \langle cdcl_{NOT}^{**} \ S \ T \rangle \ inv \ n\text{-}d \ atms\text{-}clss \ atms\text{-}trail]$
by $fast$
moreover have $no\text{-}dup \ (trail \ T)$
using $cdcl_{NOT}.rtranclp\text{-}cdcl_{NOT}\text{-}no\text{-}dup[OF \ \langle cdcl_{NOT}^{**} \ S \ T \rangle \ inv \ n\text{-}d] \ by \ fast$

obtain $F' \ K \ F \ L \ l \ C' \ C$ **where**
 $tr\text{-}S: trail \ S = F' @ Marked \ K \ () \ \# \ F$ **and**
 $T: T \sim prepend\text{-}trail \ (Propagated \ L \ l) \ (reduce\text{-}trail\text{-}to_{NOT} \ F \ (add\text{-}cls_{NOT} \ (C' + \{\#L\# \}) \ S))$ **and**
 $C \in \# \ clauses \ S$ **and**
 $trail \ S \models_{as} CNot \ C$ **and**
 $undef: undefined\text{-}lit \ F \ L$ **and**
 $atm\text{-}of \ L = atm\text{-}of \ K \vee atm\text{-}of \ L \in atms\text{-}of\text{-}msu \ (clauses \ S)$
 $\vee atm\text{-}of \ L \in atm\text{-}of \text{ ' (lits-of } F' \cup lits\text{-}of \ F)$ **and**
 $clauses \ S \models_{pm} C' + \{\#L\# \}$ **and**
 $F \models_{as} CNot \ C'$ **and**
 $dist: distinct\text{-}mset \ (C' + \{\#L\# \})$ **and**
 $tauto: \neg \ tautology \ (C' + \{\#L\# \})$ **and**
 $backjump\text{-}l\text{-}cond \ C \ C' \ L \ T$
using $\langle backjump\text{-}l \ S \ T \rangle$ **apply** ($induction \ rule: backjump\text{-}l.induct$) **by** $auto$

have $atms\text{-}of \ C' \subseteq atm\text{-}of \text{ ' (lits-of } F)$
using $\langle F \models_{as} CNot \ C' \rangle \ by \ (simp \ add: \ atm\text{-}of\text{-}in\text{-}atm\text{-}of\text{-}set\text{-}iff\text{-}in\text{-}set\text{-}or\text{-}uminus\text{-}in\text{-}set$
 $atms\text{-}of\text{-}def \ image\text{-}subset\text{-}iff \ in\text{-}CNot\text{-}implies\text{-}uminus(2))$
then have $atms\text{-}of \ (C' + \{\#L\# \}) \subseteq atms\text{-}of\text{-}ms \ A$
using $T \ \langle atm\text{-}of \text{ ' (lits-of (trail } T) \subseteq atms\text{-}of\text{-}ms \ A) \ tr\text{-}S \ undef \ n\text{-}d \ by \ auto$
then have $simple\text{-}clss \ (atms\text{-}of \ (C' + \{\#L\# \})) \subseteq simple\text{-}clss \ (atms\text{-}of\text{-}ms \ A)$
apply $- \ by \ (rule \ simple\text{-}clss\text{-}mono) \ (simp\text{-}all)$
then have $C' + \{\#L\# \} \in simple\text{-}clss \ (atms\text{-}of\text{-}ms \ A)$

```

    using distinct-mset-not-tautology-implies-in-simple-clss[OF dist tauto]
  by auto
then show ?case
  using T inv atms-clss undef tr-S n-d
  by (force dest!: simple-clss-or-not-simplified-cls)
qed

```

```

lemma cdclNOT-merged-bj-learn-not-simplified-decreasing:
  assumes cdclNOT-merged-bj-learn S T
  shows (not-simplified-cls (clauses T))  $\subseteq$  # (not-simplified-cls (clauses S))
  using assms apply induction
  prefer 4
  unfolding not-simplified-cls-def apply (auto elim!: backjump-LE forgetE)[3]
  by (elim backjump-LE) auto

```

```

lemma rtrancpl-cdclNOT-merged-bj-learn-not-simplified-decreasing:
  assumes cdclNOT-merged-bj-learn** S T
  shows (not-simplified-cls (clauses T))  $\subseteq$  # (not-simplified-cls (clauses S))
  using assms apply induction
  apply simp
  by (drule cdclNOT-merged-bj-learn-not-simplified-decreasing) auto

```

```

lemma rtrancpl-cdclNOT-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 '(lits-of (trail S))  $\subseteq$  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-cls (clauses S))
     $\cup$  simple-clss (atms-of-ms A)
  using assms(1-5)
proof induction
  case base
  then show ?case by (auto dest!: simple-clss-or-not-simplified-cls)
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 rtrancpl-cdclNOT-merged-bj-learn-is-rtrancpl-cdclNOT-and-inv st n-d by blast
  have inv T
  using inv rtrancpl-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 ' lits-of (trail T)  $\subseteq$  atms-of-ms A
  using cdclNOT.rtrancpl-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 cdclNOT.rtrancpl-cdclNOT-no-dup[OF  $\langle$ cdclNOT** S T $\rangle$  inv n-d] by fast
  ultimately have set-mset (clauses U)
     $\subseteq$  set-mset (not-simplified-cls (clauses T))  $\cup$  simple-clss (atms-of-ms A)
  using cdclNOT finite cdclNOT-merged-bj-learn-clauses-bound
  by (auto intro!: cdclNOT-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 $\text{rtrancpl-cdcl}_{NOT}\text{-merged-bj-learn-not-simplified-decreasing}[OF\ st]$ **by** *auto*
ultimately show $?case$ **using** $IH\ inv\ atms-clss-S$
by $(\text{auto } dest! : \text{simple-clss-or-not-simplified-cls})$
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 $\text{rtrancpl-cdcl}_{NOT}\text{-merged-bj-learn-clauses-bound-card}$:

assumes

$\text{cdcl}_{NOT}\text{-merged-bj-learn}^{**}\ S\ T$ **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**

$n\text{-d: no-dup } (\text{trail } S)$ **and**

$finite: finite\ A$

shows $\mu_{CDCL}'\text{-merged } A\ T \leq \mu_{CDCL}'\text{-bound } A\ S$

proof –

have $\text{set-mset } (\text{clauses } T) \subseteq \text{set-mset } (\text{not-simplified-cls}(\text{clauses } S))$

$\cup \text{simple-clss } (\text{atms-of-ms } A)$

using $\text{rtrancpl-cdcl}_{NOT}\text{-merged-bj-learn-clauses-bound}[OF\ assms]$.

moreover have $\text{card } (\text{set-mset } (\text{not-simplified-cls}(\text{clauses } S)))$

$\cup \text{simple-clss } (\text{atms-of-ms } A)$

$\leq \text{card } (\text{set-mset } (\text{not-simplified-cls}(\text{clauses } S))) + 3 \wedge \text{card } (\text{atms-of-ms } A)$

by $(\text{meson } \text{Nat.le-trans } \text{atms-of-ms-finite } \text{simple-clss-card } \text{card-Un-le } \text{finite } \text{nat-add-left-cancel-le})$

ultimately have $\text{card } (\text{set-mset } (\text{clauses } T))$

$\leq \text{card } (\text{set-mset } (\text{not-simplified-cls}(\text{clauses } S))) + 3 \wedge \text{card } (\text{atms-of-ms } A)$

by $(\text{meson } \text{Nat.le-trans } \text{atms-of-ms-finite } \text{simple-clss-finite } \text{card-mono } \text{finite-UnI } \text{finite-set-mset } \text{local.finite})$

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 $\text{cdcl}_{NOT}\text{-increasing-restarts-ops } \lambda S\ T. T \sim \text{reduce-trail-to}_{NOT} ([::'a\ list])\ S$

$\text{cdcl}_{NOT}\text{-merged-bj-learn } f$

$\lambda A\ S. \text{atms-of-msu } (\text{clauses } S) \subseteq \text{atms-of-ms } A$

$\wedge \text{atm-of } '(\text{lits-of } (\text{trail } S)) \subseteq \text{atms-of-ms } A \wedge \text{finite } A$

$\mu_{CDCL}'\text{-merged}$

$\lambda S. inv\ S \wedge \text{no-dup } (\text{trail } S)$

$\mu_{CDCL}'\text{-bound}$

apply unfold-locales

using $\text{unbounded apply simp}$

using $f\text{-ge-1 apply force}$

apply $(\text{blast } dest! : \text{cdcl}_{NOT}\text{-merged-bj-learn-is-trancpl-cdcl}_{NOT} \text{ trancpl-into-rtrancpl } \text{cdcl}_{NOT}.\text{rtrancpl-cdcl}_{NOT}\text{-trail-clauses-bound})$

apply $(\text{simp add: } \text{cdcl}_{NOT}\text{-decreasing-measure})$

using $\text{rtrancpl-cdcl}_{NOT}\text{-merged-bj-learn-clauses-bound-card}$ **apply** blast

apply $(\text{drule } \text{rtrancpl-cdcl}_{NOT}\text{-merged-bj-learn-not-simplified-decreasing})$

apply $(\text{auto } dest! : \text{simp: card-mono set-mset-mono}) []$

```

    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 rtrancpl-cdclNOT-merged-bj-learn-clauses-bound-card)
  using restart-full unfolding full1-def by (force dest!: trancpl-into-rtrancpl)+
next
case (restart-step  $m\ S\ T\ n\ U$ ) note st = this(1) and  $U = \text{this}(3)$  and  $\text{inv} = \text{this}(4)$  and
   $n\text{-d} = \text{this}(5)$  and  $\text{atms-clss} = \text{this}(6)$  and  $\text{atms-trail} = \text{this}(7)$  and  $\text{finite} = \text{this}(8)$ 
then have  $st'$ :  $cdcl_{NOT}\text{-merged-bj-learn}^{**}\ S\ T$ 
  by (blast dest: relpowp-imp-rtrancpl)
then have  $st''$ :  $cdcl_{NOT}^{**}\ S\ T$ 
  using inv  $n\text{-d}$  apply - by (rule rtrancpl-cdclNOT-merged-bj-learn-is-rtrancpl-cdclNOT) auto
have inv  $T$ 
  apply (rule rtrancpl-cdclNOT-merged-bj-learn-inv)
  using inv  $st'\ n\text{-d}$  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.rtrancpl-cdclNOT-trail-clauses-bound[OF  $st'$ ] inv atms-clss atms-trail  $n\text{-d}$ 
  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 rtrancpl-cdclNOT-merged-bj-learn-not-simplified-decreasing)
  using  $\langle (cdcl_{NOT}\text{-merged-bj-learn} \ \widetilde{\sim}\ m)\ S\ T \rangle$  by (auto dest!: relpowp-imp-rtrancpl)
ultimately have  $U\text{-S}$ : not-simplified-cls (clauses  $U$ )  $\subseteq\#$  not-simplified-cls (clauses  $S$ )
  by auto

have (set-mset (clauses  $U$ ))
   $\subseteq$  set-mset (not-simplified-cls (clauses  $U$ ))  $\cup$  simple-clss (atms-of-ms  $A$ )
apply (rule rtrancpl-cdclNOT-merged-bj-learn-clauses-bound)
  apply simp
  using  $\langle \text{inv } U \rangle$  apply simp
  using  $\langle \text{atms-of-msu (clauses } U) \subseteq \text{atms-of-ms } A \rangle$  apply simp
  using  $U$  apply simp
  using  $U$  apply simp

```

```

    using finite apply simp
  done
then have f1:  $\text{card } (\text{set-mset } (\text{clauses } U)) \leq \text{card } (\text{set-mset } (\text{not-simplified-cls } (\text{clauses } U)) \cup \text{simple-clss } (\text{atms-of-ms } A))$ 
  by (simp add: simple-clss-finite card-mono local.finite)

moreover have  $\text{set-mset } (\text{not-simplified-cls } (\text{clauses } U)) \cup \text{simple-clss } (\text{atms-of-ms } A) \subseteq \text{set-mset } (\text{not-simplified-cls } (\text{clauses } S)) \cup \text{simple-clss } (\text{atms-of-ms } A)$ 
  using U-S by auto
then have f2:
   $\text{card } (\text{set-mset } (\text{not-simplified-cls } (\text{clauses } U)) \cup \text{simple-clss } (\text{atms-of-ms } A)) \leq \text{card } (\text{set-mset } (\text{not-simplified-cls } (\text{clauses } S)) \cup \text{simple-clss } (\text{atms-of-ms } A))$ 
  by (simp add: simple-clss-finite card-mono local.finite)

moreover have  $\text{card } (\text{set-mset } (\text{not-simplified-cls } (\text{clauses } S)) \cup \text{simple-clss } (\text{atms-of-ms } A)) \leq \text{card } (\text{set-mset } (\text{not-simplified-cls } (\text{clauses } S))) + \text{card } (\text{simple-clss } (\text{atms-of-ms } A))$ 
  using card-Un-le by blast
moreover have  $\text{card } (\text{simple-clss } (\text{atms-of-ms } A)) \leq 3 \wedge \text{card } (\text{atms-of-ms } A)$ 
  using atms-of-ms-finite simple-clss-card local.finite by blast
ultimately have  $\text{card } (\text{set-mset } (\text{clauses } U)) \leq \text{card } (\text{set-mset } (\text{not-simplified-cls } (\text{clauses } S))) + 3 \wedge \text{card } (\text{atms-of-ms } A)$ 
  by linarith
then show ?case unfolding  $\mu_{CDCL}'\text{-merged-def}$  by auto
qed

lemma cdclNOT-restart- $\mu_{CDCL}'$ -bound-le- $\mu_{CDCL}'$ -bound:
  assumes
    cdclNOT-restart T V and
    no-dup (trail (fst T)) and
    inv (fst T) and
    fin: finite A
  shows  $\mu_{CDCL}'\text{-bound } A \text{ (fst } V) \leq \mu_{CDCL}'\text{-bound } A \text{ (fst } T)$ 
  using assms(1-3)
proof induction
  case (restart-full S T n)
  have  $\text{not-simplified-cls } (\text{clauses } T) \subseteq \# \text{ not-simplified-cls } (\text{clauses } S)$ 
    apply (rule rtranclp-cdclNOT-merged-bj-learn-not-simplified-decreasing)
    using  $\langle \text{full1 cdcl}_{NOT}\text{-merged-bj-learn } S \ T \rangle$  unfolding full1-def
    by (auto dest: tranclp-into-rtranclp)
  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':  $\text{cdcl}_{NOT}\text{-merged-bj-learn}^{**} S \ T$ 
    by (blast dest: relpowp-imp-rtranclp)
  then have st'':  $\text{cdcl}_{NOT}^{**} S \ T$ 
    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  $\text{not-simplified-cls } (\text{clauses } U) \subseteq \# \text{ not-simplified-cls } (\text{clauses } T)$ 
    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-cdcl_{NOT}-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) $\subseteq \#$ *not-simplified-cls* (clauses S)
by auto
then show ?case **by** (auto *simp*: *card-mono set-mset-mono*)
qed

sublocale *cdcl_{NOT}-increasing-restarts* - - - - $f \lambda S T. T \sim \text{reduce-trail-to}_{NOT} ([::'a \text{ list}] S$
 $\lambda A S. \text{atms-of-msu} (\text{clauses } S) \subseteq \text{atms-of-ms } A$
 $\wedge \text{atm-of ' lits-of } (\text{trail } S) \subseteq \text{atms-of-ms } A \wedge \text{finite } A$
 $\mu_{CDCL}'\text{-merged } cdcl_{NOT}\text{-merged-bj-learn}$
 $\lambda S. \text{inv } S \wedge \text{no-dup } (\text{trail } S)$
 $\lambda A T. ((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))) * 2$
 $+ \text{card } (\text{set-mset } (\text{not-simplified-cls}(\text{clauses } T)))$
 $+ 3 \wedge \text{card } (\text{atms-of-ms } A)$
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

cdcl_{NOT}-restart $S T$ **and**

no-dup (*trail* (*fst* S))

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 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.prem1,2*

rtranclp-cdcl_{NOT}-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.prem1,2*

rtranclp-cdcl_{NOT}-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

*cdcl_{NOT}-restart*** $S T$ **and**

inv: *inv* (*fst* S) **and** *n-d*: *no-dup*(*trail* (*fst* S))

shows $I \models_{\text{sextm}} \text{clauses } (\text{fst } S) \longleftrightarrow I \models_{\text{sextm}} \text{clauses } (\text{fst } T)$

using *assms(1)*

proof (*induction rule*: *rtranclp-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 rtranclp-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: tranclp-into-rtranclp)+
  have st': cdclNOT** S T
  using inv rtranclp-cdclNOT-merged-bj-learn-is-rtranclp-cdclNOT-and-inv st n-d by auto
  have inv T
  using rtranclp-cdclNOT-cdclNOT-inv[OF st] inv n-d by auto
  then show ?case
  using cdclNOT.rtranclp-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 rtranclp-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 = this(1) and cdcl = this(2) and IH = this(3)[OF this(4-)] and
  inv = this(4) and n-d = this(5) and decomp = this(6)
have inv (fst T) and no-dup (trail (fst T))
  using rtranclp-cdclNOT-with-restart-cdclNOT-inv using st inv n-d by blast+
then show ?case

```

using $cdcl_{NOT}$ -restart-all-decomposition-implies-m[*OF* $cdcl$] *IH* **by** *auto*
qed

lemma $full\text{-}cdcl_{NOT}$ -restart-normal-form:

assumes

full: $full\text{-}cdcl_{NOT}$ -restart *S T* **and**

inv: $inv\ (fst\ S)$ **and** *n-d*: $no\text{-}dup(trail\ (fst\ S))$ **and**

decomp: $all\text{-}decomposition\text{-}implies\text{-}m\ (clauses\ (fst\ S))$

$(get\text{-}all\text{-}marked\text{-}decomposition\ (trail\ (fst\ S)))$ **and**

atms-cls: $atms\text{-}of\text{-}msu\ (clauses\ (fst\ S)) \subseteq atms\text{-}of\text{-}ms\ A$ **and**

atms-trail: $atm\text{-}of\ 'lits\text{-}of\ (trail\ (fst\ S)) \subseteq atms\text{-}of\text{-}ms\ A$ **and**

fin: $finite\ A$

shows $unsatisfiable\ (set\text{-}mset\ (clauses\ (fst\ S)))$

$\vee\ lits\text{-}of\ (trail\ (fst\ T)) \models_{sextm}\ clauses\ (fst\ S) \wedge satisfiable\ (set\text{-}mset\ (clauses\ (fst\ S)))$

proof –

have *inv-T*: $inv\ (fst\ T)$ **and** *n-d-T*: $no\text{-}dup\ (trail\ (fst\ T))$

using $rtranclp\text{-}cdcl_{NOT}$ -with-restart- $cdcl_{NOT}$ -*inv* **using** *full inv n-d unfolding full-def* **by** *blast+*

moreover have

atms-cls-T: $atms\text{-}of\text{-}msu\ (clauses\ (fst\ T)) \subseteq atms\text{-}of\text{-}ms\ A$ **and**

atms-trail-T: $atm\text{-}of\ 'lits\text{-}of\ (trail\ (fst\ T)) \subseteq atms\text{-}of\text{-}ms\ A$

using $rtranclp\text{-}cdcl_{NOT}$ -with-restart-bound-*inv*[*of S T A*] *full atms-cls atms-trail fin inv n-d*

unfolding *full-def* **by** *blast+*

ultimately have $no\text{-}step\ cdcl_{NOT}$ -merged-bj-learn (*fst T*)

apply –

apply (*rule no-step- $cdcl_{NOT}$ -restart-no-step- $cdcl_{NOT}$ [of - A]*)

using *full unfolding full-def* **apply** *simp*

apply *simp*

using *fin* **apply** *simp*

done

moreover have $all\text{-}decomposition\text{-}implies\text{-}m\ (clauses\ (fst\ T))$

$(get\text{-}all\text{-}marked\text{-}decomposition\ (trail\ (fst\ T)))$

using $rtranclp\text{-}cdcl_{NOT}$ -restart-all-decomposition-implies-m[*of S T*] *inv n-d decomp*

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

ultimately have $unsatisfiable\ (set\text{-}mset\ (clauses\ (fst\ T)))$

$\vee\ trail\ (fst\ T) \models_{asm}\ clauses\ (fst\ T) \wedge satisfiable\ (set\text{-}mset\ (clauses\ (fst\ T)))$

apply –

apply (*rule $cdcl_{NOT}$ -merged-bj-learn-final-state*)

using *atms-cls-T atms-trail-T fin n-d-T fin inv-T* **by** *blast+*

then consider

$(unsat)\ unsatisfiable\ (set\text{-}mset\ (clauses\ (fst\ T)))$

$| (sat)\ trail\ (fst\ T) \models_{asm}\ clauses\ (fst\ T) \wedge satisfiable\ (set\text{-}mset\ (clauses\ (fst\ T)))$

by *auto*

then show $unsatisfiable\ (set\text{-}mset\ (clauses\ (fst\ S)))$

$\vee\ lits\text{-}of\ (trail\ (fst\ T)) \models_{sextm}\ clauses\ (fst\ S) \wedge satisfiable\ (set\text{-}mset\ (clauses\ (fst\ S)))$

proof *cases*

case *unsat*

then have $unsatisfiable\ (set\text{-}mset\ (clauses\ (fst\ S)))$

unfolding *satisfiable-def* **apply** *auto*

using $rtranclp\text{-}cdcl_{NOT}$ -restart-eq-sat-iff[*of S T*] *full inv n-d*

consistent-true-clss-ext-satisfiable true-clss-imp-true-cls-ext

unfolding *satisfiable-def full-def* **by** *blast*

then show *?thesis* **by** *blast*

next

case *sat*

then have $lits\text{-}of\ (trail\ (fst\ T)) \models_{sextm}\ clauses\ (fst\ T)$

```

    using true-clss-imp-true-cls-ext by (auto simp: true-annots-true-cls)
  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-cdclNOT-restart-normal-form-init-state:
  assumes
    init-state: trail S = [] clauses S = N and
    full: full cdclNOT-restart (S, 0) T and
    inv: inv S
  shows unsatisfiable (set-mset N)
     $\vee$  lits-of (trail (fst T))  $\models_{\text{sextm}}$  N  $\wedge$  satisfiable (set-mset N)
  using full-cdclNOT-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 dppll-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' @ Marked K () # F  $\wedge$ 
      M' = Propagated L l # F  $\wedge$  N = N'  $\wedge$  C  $\in$  # N  $\wedge$  F' @ Marked K d # F  $\models_{\text{as}}$  CNot C  $\wedge$ 
      undefined-lit F L  $\wedge$  atm-of L  $\in$  atms-of-msu N  $\cup$  atm-of ' lits-of (F' @ 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-sp: backtrack-split M = (F', L # F) and
      is-marked L and

```

$D \in \#$ 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 $?C = \text{image-mset } lit\text{-}of\ \{\#K \in \#mset\ M. \text{is-marked } K \wedge K \neq L\# \} :: 'v \text{ literal multiset}$
let $?C' = \text{set-mset } (\text{image-mset } single\ (?C + \{\#?K\#}))$
obtain K **where** $L: L = \text{Marked } K\ ()$ **using** $\langle \text{is-marked } L \rangle$ **by** (*cases* L) *auto*

have $M: M = F' @ \text{Marked } K\ () \# F$
using *b-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* $(-K) \in \text{atms-of-msu } N \cup \text{atm-of } ' \text{ lits-of } (F' @ \text{Marked } K\ d \# F)$
by *auto*
moreover
have *set-mset* $N \cup ?C' \models_{ps} \{\{\#\}\}$
proof –
have $A: \text{set-mset } N \cup ?C' \cup \text{unmark } M =$
 $\text{set-mset } N \cup \text{unmark } M$
unfolding $M\ L$ **by** *auto*
have *set-mset* $N \cup \{\{\#lit\text{-}of\ L\#\} \mid L. \text{is-marked } L \wedge L \in \text{set } M\}$
 $\models_{ps} \text{unmark } M$
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** $N\text{-}C\text{-}M: \text{set-mset } N \cup ?C' \models_{ps} \text{unmark } M$
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*) $\langle M \models_{as} CNot\ D \rangle$
 $\text{true-annots-true-clss } \text{true-clss-mono-set-mset-l } \text{true-clss-def}$
 $\text{true-clss-singleton-lit-of-implies-incl } \text{true-clss-union}$)
ultimately **show** $?case$ **using** *cons* *consistent-CNot-not* **by** *blast*
qed
then **show** $?thesis$
using *true-clss-clss-left-right*[*OF* $N\text{-}C\text{-}M$, *of* $\{\{\#\}\}$] **unfolding** A **by** *auto*
qed
have $N \models_{pm} \text{image-mset } uminus\ ?C + \{\#-?K\#\}$
unfolding *true-clss-clss-def* *true-clss-clss-def* *total-over-m-def*
proof (*intro* *allI* *impI*)
fix I
assume
 $tot: \text{total-over-set } I\ (\text{atms-of-ms } (\text{set-mset } N \cup \{\text{image-mset } uminus\ ?C + \{\#-?K\#\}\}))$ **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 tI: 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
  proof -
    fix x :: ('v, unit, unit) marked-lit
    assume a1: x  $\neq$  Marked K d
    assume a2: is-marked x
    assume a3: x  $\in$  set M
    assume a4: lit-of x  $\notin$  I
    have atm-of (lit-of x)  $\in$  atm-of 'lit-of'
      (set M  $\cap$  {m. is-marked m  $\wedge$  m  $\neq$  Marked K d})
      using a3 a2 a1 by blast
    then have Pos (atm-of (lit-of x))  $\in$  I  $\vee$  Neg (atm-of (lit-of x))  $\in$  I
      using tI unfolding total-over-set-def by blast
    then show - lit-of x  $\in$  I
      using a4 by (metis (no-types) atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
        literal.sel(1,2))
  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-cls-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

$\exists C F' K F L l C'$.

$\text{fst } S = F' @ \text{Marked } K () \# F \wedge$

$T = (\text{Propagated } L l \# F, \text{snd } S) \wedge C \in \# \text{snd } S \wedge \text{fst } S \models_{as} \text{CNot } C$

$\wedge \text{undefined-lit } F L \wedge \text{atm-of } L \in \text{atms-of-msu } (\text{snd } S) \cup \text{atm-of 'lits-of' } (\text{fst } S) \wedge$

$\text{snd } S \models_{pm} C' + \{\#L\# \} \wedge F \models_{as} \text{CNot } C'$

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* $\lambda L (M, N). (L \# M, N) \lambda(M, N). (tl\ M, N)$
 $\lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, remove-mset\ C\ N)$
by *unfold-locales auto*

sublocale *backjumping-ops fst snd* $\lambda L (M, N). (L \# M, N) \lambda(M, N). (tl\ M, N)$
 $\lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, remove-mset\ C\ N) \lambda - - S\ T. backtrack\ S\ T$
by *unfold-locales*

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 *backjump S T*

proof –
obtain $C\ F'\ K\ F\ L\ l\ C'$ **where**
1: $fst\ S = F' @ Marked\ K\ () \# F$ **and**
2: $T = (Propagated\ L\ l\ \# F, snd\ S)$ **and**
3: $C \in \#\ snd\ S$ **and**
4: $fst\ S \models_{as}\ CNot\ C$ **and**
5: *undefined-lit F L* **and**
6: $atm-of\ L \in atm-of-msu\ (snd\ S) \cup atm-of\ 'lits-of\ (fst\ S)$ **and**
7: $snd\ S \models_{pm}\ C' + \{\#L\#\}$ **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
 $M: fst\ S = F' @ Marked\ K\ d\ \# F$ **and**
 $C \in \#\ snd\ S$ **and**
 $C: fst\ S \models_{as}\ CNot\ C$
shows $\neg no-step\ backtrack\ S$

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*] $\langle C \in \#\ snd\ S \rangle\ C$ **unfolding** M **by** *auto*
qed

end

sublocale *dpll-with-backtrack* $\subseteq dpll-with-backjumping-ops\ fst\ snd\ \lambda L (M, N). (L \# M, N)$
 $\lambda(M, N). (tl\ M, N) \lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, remove-mset\ C\ N) \lambda - -. True$
 $\lambda(M, N). no-dup\ M \wedge all-decomposition-implies-m\ N\ (get-all-marked-decomposition\ M)$

```

λ- - 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 ⊆ dpll-with-backjumping fst snd λL (M, N). (L # M, N)
λ(M, N). (tl M, N) λC (M, N). (M, {#C#} + N) λC (M, N). (M, remove-mset C N) λ- -. True
λ(M, N). no-dup M ∧ all-decomposition-implies-m N (get-all-marked-decomposition M)
λ- - 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 ⊆ conflict-driven-clause-learning-ops
fst snd λL (M, N). (L # M, N)
λ(M, N). (tl M, N) λC (M, N). (M, {#C#} + N) λC (M, N). (M, remove-mset C N) λ- -. True
λ(M, N). no-dup M ∧ all-decomposition-implies-m N (get-all-marked-decomposition M)
λ- - S T. backtrack S T λ- -. False λ- -. False
by unfold-locales

sublocale dpll-with-backtrack ⊆ conflict-driven-clause-learning
fst snd λL (M, N). (L # M, N)
λ(M, N). (tl M, N) λC (M, N). (M, {#C#} + N) λC (M, N). (M, remove-mset C N) λ- -. True
λ(M, N). no-dup M ∧ all-decomposition-implies-m N (get-all-marked-decomposition M)
λ- - S T. backtrack S T λ- -. False λ- -. False
apply unfold-locales
using cdclNOT.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') ∧ atms-of-msu N ⊆ 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) ∨ (M' ⊨asm N ∧ 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' ⊨asm N ⟷ satisfiable (set-mset N)
proof -
  have no-dup M'
  using rtranclp-dpll-bj-no-dup[of ([], N) (M', N')]
  full unfolding full-def by auto
  then have M' ⊨asm N ⟹ satisfiable (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 *cdcl_{NOT}-is-dpll*:
 $cdcl_{NOT} S T \longleftrightarrow dpll\text{-}bj S T$
by (*auto simp: cdcl_{NOT}.simps learn.simps forget_{NOT}.simps*)

Another proof of termination:

lemma *wf* $\{(T, S). dpll\text{-}bj S T \wedge cdcl_{NOT}\text{-}NOT\text{-}all\text{-}inv A S\}$
unfolding *cdcl_{NOT}-is-dpll[symmetric]*
by (*rule wf-cdcl_{NOT}-no-learn-and-forget-infinite-chain*)
(auto simp: learn.simps forget_{NOT}.simps)
end

15.2 Adding restarts

locale *dpll-withbacktrack-and-restarts* =
dpll-with-backtrack +
fixes $f :: nat \Rightarrow nat$
assumes *unbounded*: $unbounded f$ **and** $f\text{-}ge\text{-}1 : \bigwedge n. n \geq 1 \implies f n \geq 1$
begin
sublocale *cdcl_{NOT}-increasing-restarts* *fst snd* $\lambda L (M, N). (L \# M, N) \lambda(M, N). (tl M, N)$
 $\lambda C (M, N). (M, \{\#C\} + N) \lambda C (M, N). (M, remove\text{-}mset C N) f \lambda(-, N) S. S = ([], N)$
 $\lambda A (M, N). atms\text{-}of\text{-}msu N \subseteq atms\text{-}of\text{-}ms A \wedge atm\text{-}of ' lits\text{-}of M \subseteq atms\text{-}of\text{-}ms A \wedge finite A$
 $\wedge all\text{-}decomposition\text{-}implies\text{-}m N (get\text{-}all\text{-}marked\text{-}decomposition M)$
 $\lambda A T. (2 + card (atms\text{-}of\text{-}ms A)) \wedge (1 + card (atms\text{-}of\text{-}ms A))$
 $\quad - \mu_C (1 + card (atms\text{-}of\text{-}ms A)) (2 + card (atms\text{-}of\text{-}ms A)) (trail\text{-}weight T) dpll\text{-}bj$
 $\lambda(M, N). no\text{-}dup M \wedge all\text{-}decomposition\text{-}implies\text{-}m N (get\text{-}all\text{-}marked\text{-}decomposition M)$
 $\lambda A -. (2 + card (atms\text{-}of\text{-}ms A)) \wedge (1 + card (atms\text{-}of\text{-}ms A))$
apply *unfold-locales*
apply (*rule unbounded*)
using *f-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 (*rename-tac A T U, case-tac T, simp*)
apply (*rename-tac A T U, 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 $'a$ *dpll_W-marked-lit* = $('a, unit, unit)$ *marked-lit*
type-synonym $'a$ *dpll_W-marked-lits* = $('a, unit, unit)$ *marked-lits*
type-synonym $'v$ *dpll_W-state* = $'v$ *dpll_W-marked-lits* \times $'v$ *clauses*

abbreviation *trail* $:: 'v$ *dpll_W-state* $\Rightarrow 'v$ *dpll_W-marked-lits* **where**
trail $\equiv fst$

abbreviation $clauses :: 'v \text{ dpll}_W\text{-state} \Rightarrow 'v \text{ clauses}$ **where**
 $clauses \equiv \text{snd}$

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**
 $\text{propagate: } C + \{\#L\# \} \in \# \text{ clauses } S \Longrightarrow \text{trail } S \models_{\text{as}} C \text{Not } C \Longrightarrow \text{undefined-lit } (\text{trail } S) \text{ } L$
 $\Longrightarrow \text{dpll}_W \text{ } S \text{ } (\text{Propagated } L \text{ } () \# \text{ trail } S, \text{ clauses } S) \mid$
 $\text{decided: } \text{undefined-lit } (\text{trail } S) \text{ } L \Longrightarrow \text{atm-of } L \in \text{atms-of-msu } (\text{clauses } S)$
 $\Longrightarrow \text{dpll}_W \text{ } S \text{ } (\text{Marked } L \text{ } () \# \text{ trail } S, \text{ clauses } S) \mid$
 $\text{backtrack: } \text{backtrack-split } (\text{trail } S) = (M', L \# M) \Longrightarrow \text{is-marked } L \Longrightarrow D \in \# \text{ clauses } S$
 $\Longrightarrow \text{trail } S \models_{\text{as}} C \text{Not } D \Longrightarrow \text{dpll}_W \text{ } S \text{ } (\text{Propagated } (- \text{ (lit-of } L)) \text{ } () \# M, \text{ clauses } S)$

16.2 Invariants

lemma $\text{dpll}_W\text{-distinct-inv:}$

assumes $\text{dpll}_W \text{ } S \text{ } S'$
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 ($\text{decided } L \text{ } S$)

then show $?case$ **using** $\text{defined-lit-map by force}$

next

case ($\text{propagate } C \text{ } L \text{ } S$)

then show $?case$ **using** $\text{defined-lit-map by force}$

next

case ($\text{backtrack } S \text{ } M' \text{ } L \text{ } M \text{ } D$) **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 $\text{dpll}_W \text{ } S \text{ } S'$
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 ($\text{backtrack } S \text{ } M' \text{ } L \text{ } M \text{ } D$) **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 $\text{insert } (\text{lit-of } L) \text{ } (\text{lits-of } M) \subseteq \text{lits-of } (\text{trail } S)$

using $\text{backtrack-split-list-eq[of trail } S, \text{ symmetric}]$ **unfolding** extracted by auto

then have $\text{cons: consistent-interp } (\text{insert } (\text{lit-of } L) \text{ } (\text{lits-of } M))$

using $\text{consistent-interp-subset cons by blast}$

moreover

have $\text{lit-of } L \notin \text{lits-of } M$

using $\text{no-dup backtrack-split-list-eq[of trail } S, \text{ symmetric}]$ extracted
unfolding $\text{lits-of-def by force}$

moreover

have $\text{atm-of } (-\text{lit-of } L) \notin (\lambda m. \text{atm-of } (\text{lit-of } m)) \text{ ' set } M$

using $\text{no-dup backtrack-split-list-eq[of trail } S, \text{ symmetric}]$ **unfolding** $\text{extracted by force}$

then have $-\text{lit-of } L \notin \text{lits-of } M$

unfolding $\text{lits-of-def by force}$

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 ' (lits-of (trail S)) ⊆ atms-of-msu (clauses S)*
shows *atm-of ' (lits-of (trail S')) ⊆ atms-of-msu (clauses S')*
using *assms*
proof (induct rule: *dpll_W.induct*)
case (*backtrack S M' L M D*)
then have *atm-of (lit-of L) ∈ atms-of-msu (clauses S)*
using *backtrack-split-list-eq[of trail S, symmetric]* **by** auto
moreover
have *atm-of ' lits-of (trail S) ⊆ atms-of-msu (clauses S)*
using *backtrack(5)* **by** simp
then have $\bigwedge x. x \in \text{set } M \implies \text{atm-of (lit-of } x) \in \text{atms-of-msu (clauses S)}$
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 ((λa. {#lit-of a#}) ' c) = 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 ' lits-of (trail S) ⊆ atms-of-msu (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** *inS = this(1)* **and** *cnot = this(2)* **and** *IH = this(4)* **and** *undef = this(3)* **and** *atms-incl = this(5)*
let ?*I* = *set (map (λa. {#lit-of a#}) (trail S)) ∪ set-mset (clauses S)*
have ?*I* ⊨_p *C + {#L#}* **by** (auto simp add: *inS*)
moreover have ?*I* ⊨_{ps} *CNot C* **using** *true-annots-true-clss-cls cnot* **by** fastforce
ultimately have ?*I* ⊨_p {#*L*#} **using** *true-clss-cls-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) ≠ []*
have 1: $\bigwedge a b. (a, b) \in \text{set (tl (get-all-marked-decomposition (trail S)))}$
 $\implies (\text{unmark } a \cup \text{set-mset (clauses S)}) \models_{ps} \text{unmark } b$
using *IH* **unfolding** *all-decomposition-implies-def* **by** (fastforce simp add: *list.set-sel(2) n*)
moreover have 2: $\bigwedge a c. \text{hd (get-all-marked-decomposition (trail S))} = (a, c)$
 $\implies (\text{unmark } a \cup \text{set-mset (clauses S)}) \models_{ps} (\text{unmark } c)$
by (metis *IH* *all-decomposition-implies-cons-pair* *all-decomposition-implies-single* *list.collapse n*)
moreover have 3: $\bigwedge a c. \text{hd (get-all-marked-decomposition (trail S))} = (a, c)$

```

⇒ (unmark a ∪ set-mset (clauses S)) ⊨p {#L#}
proof -
  fix a c
  assume h: hd (get-all-marked-decomposition (trail S)) = (a, c)
  have h': trail S = c @ a using get-all-marked-decomposition-decomp h by blast
  have I: set (map (λa. {#lit-of a#}) a) ∪ set-mset (clauses S)
    ∪ unmark c ⊨ps CNot C
    using (?!I ⊨ps CNot C) unfolding h' by (simp add: Un-commute Un-left-commute)
  have
    atms-of-ms (CNot C) ⊆ atms-of-ms (set (map (λa. {#lit-of a#}) a) ∪ set-mset (clauses S))
    and
    atms-of-ms (unmark c) ⊆ atms-of-ms (set (map (λa. {#lit-of a#}) a)
      ∪ set-mset (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 unmark a ∪ set-mset (clauses S) ⊨ps CNot C
    using true-clss-clss-left-right[OF - I] h 2 by auto
  then show unmark a ∪ set-mset (clauses S) ⊨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 (cases hd (get-all-marked-decomposition (trail S)))
    (auto simp: all-decomposition-implies-def)
}
ultimately show ?case by auto
next
case (backtrack S M' L M D) note extracted = this(1) and marked = this(2) and D = this(3) and
  cnot = this(4) and cons = this(4) and IH = this(5) and atms-incl = this(6)
have S: trail S = M' @ L # M
  using backtrack-split-list-eq[of trail S] unfolding extracted by auto
have M': ∀ l ∈ set M'. ¬is-marked l
  using extracted backtrack-split-fst-not-marked[of - trail S] by simp
have n: get-all-marked-decomposition (trail S) ≠ [] by auto
then have all-decomposition-implies-m (clauses S) ((L # M, M')
  # tl (get-all-marked-decomposition (trail S)))
  by (metis (no-types) IH extracted get-all-marked-decomposition-backtrack-split list.exhaust-sel)
then have 1: unmark (L # M) ∪ set-mset (clauses S) ⊨ps(λa. {#lit-of a#}) ' set M'
  by simp
moreover
  have unmark (L # M) ∪ unmark M' ⊨ps CNot D
    by (metis (mono-tags, lifting) S Un-commute cons image-Un set-append
      true-annots-true-clss-clss)
  then have 2: unmark (L # M) ∪ set-mset (clauses S) ∪ unmark 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: unmark 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  $x$ :  $x \in \text{set } (\text{get-all-marked-decomposition}$ 
     $(\text{fst } (\text{Propagated } (- \text{lit-of } L) P \# M, \text{clauses } S)))$ 
  let ? $M'$  =  $\text{Propagated } (- \text{lit-of } L) P \# M$ 
  let ? $hd$  =  $hd (\text{get-all-marked-decomposition } ?M')$ 
  let ? $tl$  =  $tl (\text{get-all-marked-decomposition } ?M')$ 
  have  $x = ?hd \vee x \in \text{set } ?tl$ 
  using  $x$ 
  by (cases  $\text{get-all-marked-decomposition } ?M'$ )
    auto
  moreover {
    assume  $x'$ :  $x \in \text{set } ?tl$ 
    have  $L'$ :  $\text{Marked } (\text{lit-of } L) () = L$  using marked by (cases  $L$ , auto)
    have  $x \in \text{set } (\text{get-all-marked-decomposition } (M' @ L \# M))$ 
      using  $x'$  get-all-marked-decomposition-except-last-choice-equal[ $\text{of } M' \text{ lit-of } L P M$ ]
       $L'$  by (metis (no-types)  $M'$  list.set-sel(2) tl-Nil)
    then have case  $x$  of ( $Ls$ , seen)  $\Rightarrow$  unmark  $Ls \cup \text{set-mset } (\text{clauses } S)$ 
       $\models_{ps}$  unmark seen
      using marked IH by (cases  $L$ ) (auto simp add:  $S$  all-decomposition-implies-def)
  }
  moreover {
    assume  $x'$ :  $x = ?hd$ 
    have  $tl$ :  $tl (\text{get-all-marked-decomposition } (M' @ L \# M)) \neq []$ 
    proof -
      have  $f1$ :  $\bigwedge ms. \text{length } (\text{get-all-marked-decomposition } (M' @ ms))$ 
         $= \text{length } (\text{get-all-marked-decomposition } ms)$ 
      by (simp add:  $M'$  get-all-marked-decomposition-remove-unmarked-length)
      have  $Suc$  ( $\text{length } (\text{get-all-marked-decomposition } M)$ )  $\neq Suc\ 0$ 
      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
       $L0$ :  $hd (tl (\text{get-all-marked-decomposition } (M' @ L \# M))) = (M0, M0')$ 
      by (cases  $hd (tl (\text{get-all-marked-decomposition } (M' @ L \# M)))$ )
    have  $x''$ :  $x = (M0, \text{Propagated } (-\text{lit-of } L) P \# M0')$ 
      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  $IL'$ : unmark  $M0 \cup \text{set-mset } (\text{clauses } S)$ 
       $\cup$  unmark  $M0' \models_{ps} \{\{\# - \text{lit-of } L\#\}\}$ 
      using  $IL$  by (simp add: Un-commute Un-left-commute image-Un)
    moreover have  $H$ : unmark  $M0 \cup \text{set-mset } (\text{clauses } S)$ 
       $\models_{ps}$  unmark  $M0'$ 
    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 $(Ls, seen) \Rightarrow unmark\ Ls \cup set\text{-}mset\ (clauses\ S)$
 $\models_{ps} unmark\ seen$
 using *true-clss-clss-left-right unfolding* x'' by *auto*
 }
 ultimately show case x of $(Ls, seen) \Rightarrow$
 $unmark\ Ls \cup set\text{-}mset\ (snd\ (?M', clauses\ S))$
 $\models_{ps} unmark\ seen$
 unfolding *snd-conv* by *blast*
 qed
 qed

Lemma theorem 2.8.3 page 72 of CW

theorem *dpll_W-propagate-is-conclusion-of-decided*:
 assumes *dpll_W S S'*
 and *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)*
shows *set-mset (clauses S') \cup { {#lit-of L#} | L. is-marked L \wedge L \in set (trail S') }*
 $\models_{ps} (\lambda a. \{ \#lit\text{-}of\ a\# \})\ ' \bigcup (set\ ' \textit{snd}\ ' set\ (get\text{-}all\text{-}marked\text{-}decomposition\ (trail\ S')))$
 using *all-decomposition-implies-trail-is-implied*[*OF dpll_W-propagate-is-conclusion*[*OF assms*]] .

Lemma theorem 2.8.4 page 72 of CW

lemma *only-propagated-vars-unsat*:
 assumes *marked: $\forall x \in set\ M. \neg is\text{-}marked\ x$*
 and *DN: $D \in N$ and $D: M \models_{as} CNot\ D$*
 and *inv: all-decomposition-implies N (get-all-marked-decomposition M)*
 and *atm-incl: atm-of ' lits-of M \subseteq atms-of-ms N*
shows *unsatisfiable N*
proof (*rule ccontr*)
 assume $\neg unsatisfiable\ N$
 then obtain *I* where
 $I: I \models_s N$ and
cons: consistent-interp I and
tot: total-over-m I N
 unfolding *satisfiable-def* by *auto*
 then have *I-D: I \models D*
 using *DN unfolding true-clss-def* by *auto*

 have *l0: { {#lit-of L#} | L. is-marked L \wedge L \in set M } = {}* using *marked* by *auto*
 have *atms-of-ms (N \cup unmark 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 \cup ($\lambda a. \{ \#lit\text{-}of\ a\# \})\ ' (set\ M))$*
 using *tot unfolding total-over-m-def* by *auto*
 then have $I \models_s (\lambda a. \{ \#lit\text{-}of\ a\# \})\ ' (set\ M)$
 using *all-decomposition-implies-propagated-lits-are-implied*[*OF inv*] *cons I*
 unfolding *true-clss-clss-def l0* by *auto*
 then have *IM: I $\models_s unmark\ M$* 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-cls-def consistent-interp-def by auto
then show False using I-D by blast
qed

lemma dpllW-same-clauses:
  assumes dpllW S S'
  shows clauses S = clauses S'
  using assms by (induct rule: dpllW.induct, auto)

lemma rtrancpl-dpllW-inv:
  assumes rtrancpl 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: rtrancpl-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 dpllW-same-clauses[OF dpllW] snd by metis

  show all-decomposition-implies-m (clauses S'') (get-all-marked-decomposition (trail S''))
    using dpllW-propagate-is-conclusion[OF dpllW] decomp atm-incl' by auto
  show atm-of ' lits-of (trail S'')  $\subseteq$  atms-of-msu (clauses S'')
    using dpllW-vars-in-snd-inv[OF dpllW] atm-incl atm-incl' by auto
  show no-dup (trail S'') using dpllW-distinct-inv[OF dpllW] no-dup' dpllW by auto
  show consistent-interp (lits-of (trail S''))
    using cons' no-dup' dpllW-consistent-interp-inv[OF dpllW] by auto
qed

```

definition $dpll_W\text{-all-inv } S \equiv$

(*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 $dpll_W\text{-all-inv-dest}[dest]:$

assumes $dpll_W\text{-all-inv } S$
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** $dpll_W\text{-all-inv-def}$ *lits-of-def* **by** *auto*

lemma $rtrancpl\text{-}dpll_W\text{-all-inv}:$

assumes $rtrancpl\text{-}dpll_W\text{-all-inv } S\ S'$
and $dpll_W\text{-all-inv } S$
shows $dpll_W\text{-all-inv } S'$
using *assms* $rtrancpl\text{-}dpll_W\text{-inv}[OF\ assms(1)]$ **unfolding** $dpll_W\text{-all-inv-def}$ *lits-of-def* **by** *blast*

lemma $dpll_W\text{-all-inv}:$

assumes $dpll_W\text{-all-inv } S\ S'$
and $dpll_W\text{-all-inv } S$
shows $dpll_W\text{-all-inv } S'$
using *assms* $rtrancpl\text{-}dpll_W\text{-all-inv}$ **by** *blast*

lemma $rtrancpl\text{-}dpll_W\text{-inv-starting-from-0}:$

assumes $rtrancpl\text{-}dpll_W\text{-all-inv } S\ S'$
and *inv*: *trail* $S = []$
shows $dpll_W\text{-all-inv } S'$

proof –

have $dpll_W\text{-all-inv } S$
using *assms* **unfolding** *all-decomposition-implies-def* $dpll_W\text{-all-inv-def}$ **by** *auto*
then show *?thesis* **using** $rtrancpl\text{-}dpll_W\text{-all-inv}[OF\ assms(1)]$ **by** *blast*

qed

lemma $dpll_W\text{-can-do-step}:$

assumes *consistent-interp* (*set* M)
and *distinct* M
and *atm-of* ‘(*set* M) \subseteq *atms-of-msu* N
shows $rtrancpl\text{-}dpll_W\text{-all-inv } ([], N)$ (*map* ($\lambda M. \text{Marked } M\ ()$) M, N)
using *assms*

proof (*induct* M)

case *Nil*
then show *?case* **by** *auto*

next

case (*Cons* $L\ M$)
then have *undefined-lit* (*map* ($\lambda M. \text{Marked } M\ ()$) M) L
unfolding *defined-lit-def* *consistent-interp-def* **by** *auto*
moreover have *atm-of* $L \in$ *atms-of-msu* N **using** *Cons.premis*(3) **by** *auto*
ultimately have $dpll_W\text{-all-inv } (\text{map } (\lambda M. \text{Marked } M\ ())\ M, N)$ (*map* ($\lambda M. \text{Marked } M\ ()$) ($L \# M$), N)
using $dpll_W\text{-decided}$ **by** *auto*
moreover have *consistent-interp* (*set* M) **and** *distinct* M **and** *atm-of* ‘*set* $M \subseteq$ *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
 $(\text{trail } S \models_{asm} \text{clauses } S \vee ((\forall L \in \text{set } (\text{trail } S)). \neg \text{is-marked } L)$
 $\wedge (\exists C \in \# \text{ clauses } S. \text{trail } S \models_{as} C \text{Not } C)))$

lemma *dpll_W-strong-completeness*:

assumes $\text{set } M \models_{sm} N$
and *consistent-interp* ($\text{set } M$)
and *distinct* M
and *atm-of* ' ($\text{set } M \subseteq \text{atms-of-msu } N$)
shows $\text{dpll}_W^{**} ([], N) (\text{map } (\lambda M. \text{Marked } M ()) M, N)$
and *conclusive-dpll_W-state* ($\text{map } (\lambda M. \text{Marked } M ()) M, N$)

proof –

show *rtrancpl* $\text{dpll}_W ([], N) (\text{map } (\lambda M. \text{Marked } M ()) M, N)$ **using** *dpll_W-can-do-step* *assms* **by** *auto*
have $\text{map } (\lambda M. \text{Marked } M ()) M \models_{asm} N$ **using** *assms*(1) *true-annots-marked-true-cls* **by** *auto*
then show *conclusive-dpll_W-state* ($\text{map } (\lambda M. \text{Marked } M ()) M, N$)
unfolding *conclusive-dpll_W-state-def* **by** *auto*

qed

lemma *dpll_W-sound*:

assumes
rtrancpl $\text{dpll}_W ([], N) (M, N)$ **and**
 $\forall S. \neg \text{dpll}_W (M, N) S$
shows $M \models_{asm} N \longleftrightarrow \text{satisfiable } (\text{set-mset } N)$ (**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 *rtrancpl-dpll_W-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 $(\exists L. \text{undefined-lit } M L \wedge \text{atm-of } L \in \text{atms-of-msu } N) \vee (\exists D \in \# N. M \models_{as} C \text{Not } D)$
proof –
obtain $D :: 'a \text{ clause}$ **where** $D: D \in \# N$ **and** $\neg M \models_a D$
using n **unfolding** *true-annots-def Ball-def* **by** *auto*
then have $(\exists L. \text{undefined-lit } M L \wedge \text{atm-of } L \in \text{atms-of } D) \vee M \models_{as} C \text{Not } D$
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*
by (*metis Bex-mset-def D atms-of-atms-of-ms-mono mem-set-mset-iff rev-subsetD*)

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 $\exists D \in \# N. M \models_{as} C \text{Not } D$
then obtain D **where** $DN: D \in \# N$ **and** $MD: M \models_{as} C \text{Not } D$ **by** *auto*


```

{
  assume  $\forall l \in \text{set } M. \neg \text{is-marked } l$ 
  moreover have  $\text{dpll}_W\text{-all-inv } ([], N)$ 
    using assms unfolding all-decomposition-implies-def dpllW-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-dpllW-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 $\text{dpll}_W\text{-mes } M \ n =$
 $\text{map } (\lambda l. \text{if is-marked } l \text{ then } 2 \text{ else } (1::\text{nat})) (\text{rev } M) @ \text{replicate } (n - \text{length } M) \ 3$

lemma *length-dpll_W-mes*:
assumes $\text{length } M \leq n$
shows $\text{length } (\text{dpll}_W\text{-mes } M \ n) = n$
using *assms unfolding dpll_W-mes-def* by *auto*

lemma *distinctcard-atm-of-lits-of-eq-length*:
assumes *no-dup S*
shows $\text{card } (\text{atm-of 'lits-of } S) = \text{length } S$
using *assms* by (*induct S*) (*auto simp add: image-image lits-of-def*)

lemma *dpll_W-card-decrease*:
assumes *dpll: dpll_W S S'* **and** $\text{length } (\text{trail } S') \leq \text{card vars}$
and $\text{length } (\text{trail } S) \leq \text{card vars}$
shows $(\text{dpll}_W\text{-mes } (\text{trail } S') (\text{card vars}), \text{dpll}_W\text{-mes } (\text{trail } S) (\text{card vars}))$
 $\in \text{lexn } \{(a, b). a < b\} (\text{card vars})$
using *assms*

proof (*induct rule: dpll_W.induct*)
case (*propagate C L S*)
have $m: \text{map } (\lambda l. \text{if is-marked } l \text{ then } 2 \text{ else } 1) (\text{rev } (\text{trail } S))$
 $@ \text{replicate } (\text{card vars} - \text{length } (\text{trail } S)) \ 3$
 $= \text{map } (\lambda l. \text{if is-marked } l \text{ then } 2 \text{ else } 1) (\text{rev } (\text{trail } S)) @ 3$
 $\# \text{replicate } (\text{card vars} - \text{Suc } (\text{length } (\text{trail } S))) \ 3$
using *propagate.prem[simplified]* **using** *Suc-diff-le* by *fastforce*
then show *?case*
using *propagate.prem(1) unfolding dpll_W-mes-def* by (*fastforce simp add: lexn-conv assms(2)*)
next
case (*decided S L*)
have $m: \text{map } (\lambda l. \text{if is-marked } l \text{ then } 2 \text{ else } 1) (\text{rev } (\text{trail } S))$
 $@ \text{replicate } (\text{card vars} - \text{length } (\text{trail } S)) \ 3$

```

= map (λl. if is-marked l then 2 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) ⊆ 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)))) ∈ 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) ≤ 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') ⊆ 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') ≤ 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'))))
  ∈ lex {(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')))) ∈ lex {(a, b). a < b}
  unfolding lex-def by auto
then show (dpllW-mes (trail S') (card (atms-of-msu (clauses S'))),
  dpllW-mes (trail S) (card (atms-of-msu (clauses S')))) ∈ lex {(a, b). a < b}
  using dpllW-same-clauses[OF assms(1)] by auto
qed

```

lemma *wf-lexn*: wf (lexn {(a, b). (a::nat) < b} (card (atms-of-msu (clauses S))))

proof –

```

have m: {(a, b). a < b} = measure id by auto
show ?thesis apply (rule wf-lexn) unfolding m by auto
qed

```

lemma *dpll_W-wf*:

$wf \{(S', S). dpll_W\text{-all-inv } S \wedge dpll_W S S'\}$
apply (rule $wf\text{-wf-if-measure}'[OF \text{ wf-lex-less, of - -}$
 $\lambda S. dpll_W\text{-mes (trail } S) (card (atms\text{-of-msu (clauses } S)))]$)
using $dpll_W\text{-card-decrease}'$ **by** fast

lemma $dpll_W\text{-trancpl-star-commute}$:

$\{(S', S). dpll_W\text{-all-inv } S \wedge dpll_W S S'\}^+ = \{(S', S). dpll_W\text{-all-inv } S \wedge \text{trancpl } dpll_W S S'\}$
 (is $?A = ?B$)

proof

{ fix $S S'$
assume $(S, S') \in ?A$
then have $(S, S') \in ?B$
by (induct rule: $\text{trancpl.induct, auto}$)
}
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: trancpl.induct)
case $r\text{-into-trancpl}$
then show $?case$ **by** (simp-all add: $r\text{-into-trancpl}'$)
next
case ($\text{trancpl-into-trancpl } S S' S''$)
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 $\text{rtrancpl-dpll}_W\text{-all-inv}[OF \text{ trancpl-into-rtrancpl}[OF \text{ trancpl-into-trancpl.hyps}(1)]]$
trancpl-into-trancpl.premis **by** auto
ultimately have $(S'', S') \in \{(pa, p). dpll_W\text{-all-inv } p \wedge dpll_W p pa\}^+$
using $\langle dpll_W\text{-all-inv } S' \rangle \text{trancpl-into-trancpl.hyps}(3)$ **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 $dpll_W\text{-wf-trancpl}$: $wf \{(S', S). dpll_W\text{-all-inv } S \wedge dpll_W^{++} S S'\}$

unfolding $dpll_W\text{-trancpl-star-commute}[\text{symmetric}]$ **by** (simp add: $dpll_W\text{-wf wf-trancpl}$)

lemma $dpll_W\text{-wf-plus}$:

shows $wf \{(S', ([], N)) | S'. dpll_W^{++} ([], N) S'\}$ (is $wf ?P$)
apply (rule $wf\text{-subset}[OF dpll_W\text{-wf-trancpl, of } ?P]$)
using $\text{assms unfolding } dpll_W\text{-all-inv-def}$ **by** auto

16.4 Final States

lemma $dpll_W\text{-no-more-step-is-a-conclusive-state}$:

assumes $\forall S'. \neg dpll_W S S'$
shows $\text{conclusive-dpll}_W\text{-state } S$

proof —

have $\text{vars: } \forall s \in \text{atms-of-msu (clauses } S). s \in \text{atm-of ' lits-of (trail } S)$
proof (rule ccontr)
assume $\neg (\forall s \in \text{atms-of-msu (clauses } S). s \in \text{atm-of ' lits-of (trail } S))$
then obtain L **where**

```

    L-in-atms:  $L \in \text{atms-of-msu}(\text{clauses } S)$  and
    L-notin-trail:  $L \notin \text{atm-of } \text{' lits-of } (\text{trail } S)$  by metis
obtain  $L'$  where  $L': \text{atm-of } L' = L$  by (meson literal.sel(2))
then have undefined-lit ( $\text{trail } S$ )  $L'$ 
    unfolding Marked-Propagated-in-iff-in-lits-of by (metis L-notin-trail atm-of-uminus imageI)
then show False using  $\text{dpll}_W.\text{decided assms}(1)$   $L\text{-in-atms } L'$  by blast
qed
show ?thesis
proof (rule ccontr)
    assume not-final:  $\neg ?thesis$ 
    then have
         $\neg \text{trail } S \models_{asm} \text{clauses } S$  and
         $(\exists L \in \text{set } (\text{trail } S). \text{is-marked } L) \vee (\forall C \in \# \text{clauses } S. \neg \text{trail } S \models_{as} CNot\ C)$ 
        unfolding conclusive-dpllW-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  $\neg \text{trail } S \models_{asm} \text{clauses } S$  unfolding true-annots-def by auto
        then have  $\forall s \in \text{atms-of-ms } \{D\}. s \in \text{atm-of } \text{' lits-of } (\text{trail } S)$ 
            using vars unfolding atms-of-ms-def by auto
        then have  $\text{trail } S \models_{as} CNot\ D$ 
            using all-variables-defined-not-imply-cnot[of D]  $\neg \text{trail } S \models_a D$  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  $\text{assms}(1)$   $\text{dpll}_W.\text{backtrack } L \langle D \in \# \text{clauses } S \rangle \langle \text{trail } S \models_{as} CNot\ D \rangle$  by blast
    }
    moreover {
        assume  $tr: \forall C \in \# \text{clauses } S. \neg \text{trail } S \models_{as} CNot\ C$ 
        obtain  $C$  where  $C\text{-in-cls}: C \in \# \text{clauses } S$  and  $trC: \neg \text{trail } S \models_a C$ 
            using  $\neg \text{trail } S \models_{asm} \text{clauses } S$  unfolding true-annots-def by auto
        have  $\forall s \in \text{atms-of-ms } \{C\}. s \in \text{atm-of } \text{' lits-of } (\text{trail } S)$ 
            using vars  $\langle C \in \# \text{clauses } S \rangle$  unfolding atms-of-ms-def by auto
        then have  $\text{trail } S \models_{as} CNot\ C$ 
            by (meson C-in-cls tr trC all-variables-defined-not-imply-cnot)
        then have False using  $tr\ C\text{-in-cls}$  by auto
    }
    ultimately show False by blast
qed
qed

lemma dpllW-conclusive-state-correct:
    assumes  $\text{dpll}_W^{**} ([], N) (M, N)$  and conclusive-dpllW-state  $(M, N)$ 
    shows  $M \models_{asm} N \longleftrightarrow \text{satisfiable } (\text{set-mset } N)$  (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 rtrancpl-dpllW-all-inv[OF assms(1)]
    unfolding dpllW-all-inv-def by force
  then show False using ⟨?B⟩ 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 rtrancpl-dpllW-rtrancpl-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 (auto intro: rtrancpl-dpllW-all-inv dpllW-dpllW-bj rtrancpl.rtrancpl-into-rtrancpl)

```

```

lemma rtrancpl-dpll-rtrancpl-dpllW:
  assumes dpllW-NOT.dpll-bj** S T and dpllW-all-inv S

```

```

shows  $dpll_W^{**} S T$ 
using assms apply (induction)
apply simp
by (auto intro: dpll_W-bj-dpll rtrancpl.rtrancpl-into-rtrancpl rtrancpl-dpll_W-all-inv)

lemma dpll-conclusive-state-correctness:
  assumes  $dpll_{W-NOT}.dpll\_bj^{**} ([], N) (M, N)$  and conclusive-dpll_W-state ( $M, N$ )
  shows  $M \models_{asm} N \longleftrightarrow \text{satisfiable } (\text{set-mset } N)$ 
proof -
  have  $dpll_W\text{-all-inv } ([], N)$ 
    unfolding dpll_W-all-inv-def by auto
  show ?thesis
    apply (rule dpll_W-conclusive-state-correct)
    apply (simp add: dpll_W-all-inv ([], N) assms(1) rtrancpl-dpll-rtrancpl-dpll_W)
    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, nat, 'a) marked-lits  $\Rightarrow$  nat  $\Rightarrow$  'v literal  $\Rightarrow$  nat where
get-rev-level [] - = 0 |
get-rev-level (Marked l level # Ls) n L =
  (if atm-of l = atm-of L then level else get-rev-level Ls level L) |
get-rev-level (Propagated l - # Ls) n L =
  (if atm-of l = atm-of L then n else get-rev-level Ls n L)

```

abbreviation *get-level* $M L \equiv \text{get-rev-level } (\text{rev } M) 0 L$

lemma *get-rev-level-uminus[simp]*: $\text{get-rev-level } M n (-L) = \text{get-rev-level } M n L$
by (*induct arbitrary: n rule: get-rev-level.induct*) *auto*

lemma *atm-of-notin-get-rev-level-eq-0[simp]*:
assumes $\text{atm-of } L \notin \text{atm-of ' lits-of } M$
shows $\text{get-rev-level } M n L = 0$
using *assms* **by** (*induct M arbitrary: n rule: marked-lit-list-induct*) *auto*

lemma *get-rev-level-ge-0-atm-of-in*:
assumes $\text{get-rev-level } M n L > n$
shows $\text{atm-of } L \in \text{atm-of ' lits-of } M$
using *assms* **by** (*induct M arbitrary: n rule: marked-lit-list-induct*) *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 $\text{atm-of } L \notin \text{atm-of ' lits-of } M$
shows $\text{get-rev-level } (M @ \text{Marked } K i \# M') n L = \text{get-rev-level } (\text{Marked } K i \# M') i L$
using *assms* **by** (*induct M arbitrary: n i rule: marked-lit-list-induct*) *auto*

lemma *get-rev-level-notin-end[simp]*:
assumes $\text{atm-of } L \notin \text{atm-of ' lits-of } M'$
shows $\text{get-rev-level } (M @ M') \ n \ L = \text{get-rev-level } M \ n \ L$
using *assms by (induct M arbitrary: n rule: marked-lit-list-induct) auto*

If the literal is at the beginning, then the end can be skipped

lemma *get-rev-level-skip-end[simp]*:
assumes $\text{atm-of } L \in \text{atm-of ' lits-of } M$
shows $\text{get-rev-level } (M @ M') \ n \ L = \text{get-rev-level } M \ n \ L$
using *assms by (induct arbitrary: n rule: marked-lit-list-induct) auto*

lemma *get-level-skip-beginning*:
assumes $\text{atm-of } L' \neq \text{atm-of (lit-of } K)$
shows $\text{get-level } (K \# M) \ L' = \text{get-level } M \ L'$
using *assms by auto*

lemma *get-level-skip-beginning-not-marked-rev*:
assumes $\text{atm-of } L \notin \text{atm-of ' lit-of ' (set } S)$
and $\forall s \in \text{set } S. \neg \text{is-marked } s$
shows $\text{get-level } (M @ \text{rev } S) \ L = \text{get-level } M \ L$
using *assms by (induction S rule: marked-lit-list-induct) auto*

lemma *get-level-skip-beginning-not-marked[simp]*:
assumes $\text{atm-of } L \notin \text{atm-of ' lit-of ' (set } S)$
and $\forall s \in \text{set } S. \neg \text{is-marked } s$
shows $\text{get-level } (M @ S) \ L = \text{get-level } M \ L$
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 $\text{atm-of } L \notin \text{atm-of ' lit-of ' (set } S)$
and $\forall s \in \text{set } S. \neg \text{is-marked } s$
shows $\text{get-rev-level } (\text{rev } S @ \text{rev } M) \ 0 \ L = \text{get-level } M \ L$
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 $\text{get-rev-level } M \ n \ L = n$
using *assms by (induction M rule: marked-lit-list-induct) auto*

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 $\text{get-level } M \ L = 0$
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 $M\text{Max } M \equiv \text{Max } (\text{set-mset } M)$

the $\{\#0::'a\# \}$ is there to ensures that the set is not empty.

definition *get-maximum-level* :: ('a, nat, 'b) marked-lit list \Rightarrow 'a literal multiset \Rightarrow nat
where
get-maximum-level M D = MMax ({#0#} + image-mset (get-level M) D)

lemma *get-maximum-level-ge-get-level*:
 $L \in \# D \Rightarrow \text{get-maximum-level } M D \geq \text{get-level } M L$
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*:
 $D \neq \{\#\} \Rightarrow \exists L \in \# D. \text{get-level } M L = \text{get-maximum-level } M D$
unfolding *get-maximum-level-def*
apply (induct D)
apply simp
by (rename-tac D x, 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]*:
 $\text{get-maximum-level } M \{\#L\# \} = \text{get-level } M L$
unfolding *get-maximum-level-def* **by** simp

lemma *get-maximum-level-plus*:
 $\text{get-maximum-level } M (D + D') = \max (\text{get-maximum-level } M D) (\text{get-maximum-level } M D')$
by (induct D) (auto simp add: get-maximum-level-def)

lemma *get-maximum-level-exists-lit*:
assumes n: $n > 0$
and max: $\text{get-maximum-level } M D = n$
shows $\exists L \in \# D. \text{get-level } M L = n$
proof –
have f: finite (insert 0 (($\lambda L. \text{get-level } M L$) ' set-mset D)) **by** auto
then have $n \in ((\lambda L. \text{get-level } M L) ' \text{set-mset } D)$
using n max Max-in[OF f] **unfolding** *get-maximum-level-def* **by** simp
then show $\exists L \in \# D. \text{get-level } M L = n$ **by** auto
qed

lemma *get-maximum-level-skip-first[simp]*:
assumes atm-of L \notin atms-of D
shows $\text{get-maximum-level } (\text{Propagated } L C \# M) D = \text{get-maximum-level } M D$
using asms **unfolding** *get-maximum-level-def* *atms-of-def*
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)
multiset.map-cong0)

lemma *get-maximum-level-skip-beginning*:
assumes DH: atms-of D \subseteq atm-of 'lits-of H
shows $\text{get-maximum-level } (c @ \text{Marked } Kh \ i \ \# H) D = \text{get-maximum-level } H D$
proof –

have (get-rev-level (rev H @ Marked Kh i # rev c) 0) ‘ set-mset D
 = (get-rev-level (rev H) 0) ‘ 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)+
then show ?thesis **using** DH **unfolding** get-maximum-level-def **by** auto
qed

lemma get-maximum-level-D-single-propagated:
 get-maximum-level [Propagated x21 x22] D = 0

proof –

have A: insert 0 ((λL. 0) ‘ (set-mset D ∩ {L. atm-of x21 = atm-of L}))
 ∪ (λL. 0) ‘ (set-mset D ∩ {L. atm-of x21 ≠ 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: ∀ L ∈ #D. atm-of L ∈ atm-of ‘ lits-of M
shows get-maximum-level M D = get-maximum-level (Propagated x21 x22 # M) D

proof –

have A: (get-rev-level (rev M @ [Propagated x21 x22]) 0) ‘ set-mset D
 = (get-rev-level (rev M) 0) ‘ 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: A)
qed

lemma get-maximum-level-skip-un-marked-not-present:

assumes ∀ L ∈ #D. atm-of L ∈ atm-of ‘ lits-of aa **and**
 ∀ m ∈ set M. ¬ is-marked m
shows get-maximum-level aa D = get-maximum-level (M @ aa) D
using assms **by** (induction M rule: marked-lit-list-induct)
 (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')
by (induct M rule: marked-lit-list-induct) auto

lemma get-maximum-possible-level-rev[simp]:

get-maximum-possible-level (rev M) = get-maximum-possible-level M
by (induct M rule: marked-lit-list-induct) auto

lemma get-maximum-possible-level-ge-get-rev-level:

max (get-maximum-possible-level M) i ≥ get-rev-level M i L
by (induct M arbitrary: i rule: marked-lit-list-induct) (auto simp add: le-max-iff-disj)

lemma get-maximum-possible-level-ge-get-level[simp]:

get-maximum-possible-level M ≥ get-level M L
using get-maximum-possible-level-ge-get-rev-level[of rev - 0] **by** auto

lemma *get-maximum-possible-level-ge-get-maximum-level[simp]*:
get-maximum-possible-level $M \geq$ *get-maximum-level* M D
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
by (*induct* A *rule: marked-lit-list-induct*) *auto*

16.5.2 Properties about the levels

fun *get-all-levels-of-marked* :: ($'b, 'a, 'c$) *marked-lit list* \Rightarrow $'a$ *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 $xs = [] \longleftrightarrow (\forall x \in \text{set } xs. \neg \text{is-marked } x)$
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 (*cases* a) *simp-all*

lemma *get-all-levels-of-marked-append[simp]*:
get-all-levels-of-marked ($a @ b$) = *get-all-levels-of-marked* $a @$ *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 $?B$

then show $?A$ **by** *auto*

next

assume $?A$

then show $?B$

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*:
get-rev-level M n $L \leq \text{Max } (\text{set } (n \# \text{get-all-levels-of-marked } M))$
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* $L \in \text{atm-of ' lits-of } M$
shows *get-rev-level* M n $L \geq \text{Min } (\text{set } (n \# \text{get-all-levels-of-marked } M))$

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]*:
get-all-levels-of-marked (*rev* *M*) = *rev* (*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*:
get-maximum-possible-level *M* = *Max* (*insert* 0 (*set* (*get-all-levels-of-marked* *M*)))
by (*induct* *M* *rule*: *marked-lit-list-induct*) (*auto simp*: *insert-commute*)

lemma *get-rev-level-in-levels-of-marked*:
get-rev-level *M* *n* *L* ∈ {0, *n*} ∪ *set* (*get-all-levels-of-marked* *M*)
by (*induction* *M* *arbitrary*: *n* *rule*: *marked-lit-list-induct*) (*force simp add*: *atm-of-eq-atm-of*) +

lemma *get-rev-level-in-atms-in-levels-of-marked*:
atm-of *L* ∈ *atm-of* ' (*lits-of* *M*) \implies *get-rev-level* *M* *n* *L* ∈ {*n*} ∪ *set* (*get-all-levels-of-marked* *M*)
by (*induction* *M* *arbitrary*: *n* *rule*: *marked-lit-list-induct*) (*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 *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*:
get-level *M* *L* ∈ {0} ∪ *set* (*get-all-levels-of-marked* *M*)
using *get-rev-level-in-levels-of-marked[of rev M 0 L]* **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 *atm-of* *L* \notin *atm-of* ' (*lits-of* *M*)
shows *get-level* (*K* @ *M*) *L* = *get-rev-level* (*rev* *K*) (*last* (0 # *get-all-levels-of-marked* (*rev* *M*)))
L

using *assms*

proof (*induct* *M* *arbitrary*: *K*)

case *Nil*

then show ?*case* **by** *auto*

next

case (*Cons* *a* *M*)

then have *H*: $\bigwedge K. \text{get-level } (K @ M) L$

= *get-rev-level* (*rev* *K*) (*last* (0 # *get-all-levels-of-marked* (*rev* *M*))) *L*

by *auto*

have *get-level* ((*K* @ [*a*]) @ *M*) *L*

= *get-rev-level* (*a* # *rev* *K*) (*last* (0 # *get-all-levels-of-marked* (*rev* *M*))) *L*

using *H[of K @ [a]]* **by** *simp*

then show ?*case* **using** *Cons(2)* **by** (*cases* *a*) *auto*

qed

lemma *get-rev-level-can-skip-correctly-ordered*:

assumes

no-dup *M* **and**

atm-of *L* \notin *atm-of* ' (*lits-of* *M*) **and**

get-all-levels-of-marked *M* = *rev* [*Suc* 0..*Suc* (*length* (*get-all-levels-of-marked* *M*))]

shows *get-rev-level* (*rev* *M* @ *K*) 0 *L* = *get-rev-level* *K* (*length* (*get-all-levels-of-marked* *M*)) *L*

```

using assms
proof (induct M arbitrary: K rule: marked-lit-list-induct)
  case nil
  then show ?case by simp
next
  case (marked L' i M K)
  then have
    i: i = Suc (length (get-all-levels-of-marked M)) and
    get-all-levels-of-marked M = rev [Suc 0..<Suc (length (get-all-levels-of-marked M))]
    by auto
  then have get-rev-level (rev M @ (Marked L' i # K)) 0 L
    = get-rev-level (Marked L' i # K) (length (get-all-levels-of-marked M)) L
    using marked by auto
  then show ?case using marked unfolding i by auto
next
  case (proped L' D M K)
  then have get-all-levels-of-marked M = rev [Suc 0..<Suc (length (get-all-levels-of-marked M))]
    by auto
  then have get-rev-level (rev M @ (Propagated L' D # K)) 0 L
    = get-rev-level (Propagated L' D # K) (length (get-all-levels-of-marked M)) L
    using proped by auto
  then show ?case using proped by auto
qed

lemma get-level-skip-beginning-hd-get-all-levels-of-marked:
  assumes atm-of L ∉ atm-of ' lits-of S
  and get-all-levels-of-marked S ≠ []
  shows get-level (M@ S) L = get-rev-level (rev M) (hd (get-all-levels-of-marked S)) L
  using assms
proof (induction S arbitrary: M rule: marked-lit-list-induct)
  case nil
  then show ?case by (auto simp add: lits-of-def)
next
  case (marked K m) note notin = this(2)
  then show ?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]: (∃ x∈set-mset C. P) ⟷ (∃ x∈#C. P)
  by auto

```

17 Weidenbach's CDCL

```

sledgehammer-params[verbose, e spass cvc4 z3 verit]
declare upt.simps(2)[simp del]

```

17.1 The State

locale *state_W* =

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 option **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 :: '*v* clause \Rightarrow '*st* \Rightarrow '*st* **and**
remove-clss :: '*v* clause \Rightarrow '*st* \Rightarrow '*st* **and**
update-backtrack-lvl :: *nat* \Rightarrow '*st* \Rightarrow '*st* **and**
update-conflicting :: '*v* clause option \Rightarrow '*st* \Rightarrow '*st* **and**

init-state :: '*v* clauses \Rightarrow '*st* **and**
restart-state :: '*st* \Rightarrow '*st*

assumes

trail-cons-trail[simp]:
 $\bigwedge L \text{ st. } \text{undefined-lit } (\text{trail st}) (\text{lit-of } L) \Longrightarrow \text{trail } (\text{cons-trail } L \text{ st}) = L \# \text{trail st} \text{ and}$
trail-tl-trail[simp]: $\bigwedge \text{st. trail } (\text{tl-trail st}) = \text{tl } (\text{trail st}) \text{ and}$
trail-add-init-clss[simp]:
 $\bigwedge \text{st } C. \text{no-dup } (\text{trail st}) \Longrightarrow \text{trail } (\text{add-init-clss } C \text{ st}) = \text{trail st} \text{ and}$
trail-add-learned-clss[simp]:
 $\bigwedge C \text{ st. no-dup } (\text{trail st}) \Longrightarrow \text{trail } (\text{add-learned-clss } C \text{ st}) = \text{trail st} \text{ and}$
trail-remove-clss[simp]:
 $\bigwedge C \text{ st. trail } (\text{remove-clss } C \text{ st}) = \text{trail st} \text{ and}$
trail-update-backtrack-lvl[simp]: $\bigwedge \text{st } C. \text{trail } (\text{update-backtrack-lvl } C \text{ st}) = \text{trail st} \text{ and}$
trail-update-conflicting[simp]: $\bigwedge C \text{ st. trail } (\text{update-conflicting } C \text{ st}) = \text{trail st} \text{ and}$

init-clss-cons-trail[simp]:
 $\bigwedge M \text{ st. undefined-lit } (\text{trail st}) (\text{lit-of } M) \Longrightarrow \text{init-clss } (\text{cons-trail } M \text{ st}) = \text{init-clss st} \text{ and}$
init-clss-tl-trail[simp]:
 $\bigwedge \text{st. init-clss } (\text{tl-trail st}) = \text{init-clss st} \text{ and}$
init-clss-add-init-clss[simp]:
 $\bigwedge \text{st } C. \text{no-dup } (\text{trail st}) \Longrightarrow \text{init-clss } (\text{add-init-clss } C \text{ st}) = \{\#C\# \} + \text{init-clss st} \text{ and}$
init-clss-add-learned-clss[simp]:
 $\bigwedge C \text{ st. no-dup } (\text{trail st}) \Longrightarrow \text{init-clss } (\text{add-learned-clss } C \text{ st}) = \text{init-clss st} \text{ and}$
init-clss-remove-clss[simp]:
 $\bigwedge C \text{ st. init-clss } (\text{remove-clss } C \text{ st}) = \text{remove-mset } C (\text{init-clss st}) \text{ and}$
init-clss-update-backtrack-lvl[simp]:
 $\bigwedge \text{st } C. \text{init-clss } (\text{update-backtrack-lvl } C \text{ st}) = \text{init-clss st} \text{ and}$
init-clss-update-conflicting[simp]:
 $\bigwedge C \text{ st. init-clss } (\text{update-conflicting } C \text{ st}) = \text{init-clss st} \text{ and}$

learned-clss-cons-trail[simp]:
 $\bigwedge M \text{ st. undefined-lit } (\text{trail st}) (\text{lit-of } M) \Longrightarrow$
 $\text{learned-clss } (\text{cons-trail } M \text{ st}) = \text{learned-clss st} \text{ and}$
learned-clss-tl-trail[simp]:
 $\bigwedge \text{st. learned-clss } (\text{tl-trail st}) = \text{learned-clss st} \text{ and}$
learned-clss-add-init-clss[simp]:
 $\bigwedge \text{st } C. \text{no-dup } (\text{trail st}) \Longrightarrow \text{learned-clss } (\text{add-init-clss } C \text{ st}) = \text{learned-clss st} \text{ and}$

learned-clss-add-learned-cls[simp]:
 $\bigwedge C \text{ st. no-dup } (\text{trail } st) \implies \text{learned-clss } (\text{add-learned-cls } C \text{ st}) = \{\#C\# \} + \text{learned-clss } st$
and
learned-clss-remove-cls[simp]:
 $\bigwedge C \text{ st. learned-clss } (\text{remove-cls } C \text{ st}) = \text{remove-mset } C \text{ (learned-clss } st) \text{ and}$
learned-clss-update-backtrack-lvl[simp]:
 $\bigwedge st \text{ C. learned-clss } (\text{update-backtrack-lvl } C \text{ st}) = \text{learned-clss } st \text{ and}$
learned-clss-update-conflicting[simp]:
 $\bigwedge C \text{ st. learned-clss } (\text{update-conflicting } C \text{ st}) = \text{learned-clss } st \text{ and}$

backtrack-lvl-cons-trail[simp]:
 $\bigwedge M \text{ st. undefined-lit } (\text{trail } st) \text{ (lit-of } M) \implies$
 $\text{backtrack-lvl } (\text{cons-trail } M \text{ st}) = \text{backtrack-lvl } st \text{ and}$
backtrack-lvl-tl-trail[simp]:
 $\bigwedge st. \text{backtrack-lvl } (\text{tl-trail } st) = \text{backtrack-lvl } st \text{ and}$
backtrack-lvl-add-init-cls[simp]:
 $\bigwedge st \text{ C. no-dup } (\text{trail } st) \implies \text{backtrack-lvl } (\text{add-init-cls } C \text{ st}) = \text{backtrack-lvl } st \text{ and}$
backtrack-lvl-add-learned-cls[simp]:
 $\bigwedge C \text{ st. no-dup } (\text{trail } st) \implies \text{backtrack-lvl } (\text{add-learned-cls } C \text{ st}) = \text{backtrack-lvl } st \text{ and}$
backtrack-lvl-remove-cls[simp]:
 $\bigwedge C \text{ st. backtrack-lvl } (\text{remove-cls } C \text{ st}) = \text{backtrack-lvl } st \text{ and}$
backtrack-lvl-update-backtrack-lvl[simp]:
 $\bigwedge st \text{ k. backtrack-lvl } (\text{update-backtrack-lvl } k \text{ st}) = k \text{ and}$
backtrack-lvl-update-conflicting[simp]:
 $\bigwedge C \text{ st. backtrack-lvl } (\text{update-conflicting } C \text{ st}) = \text{backtrack-lvl } st \text{ and}$

conflicting-cons-trail[simp]:
 $\bigwedge M \text{ st. undefined-lit } (\text{trail } st) \text{ (lit-of } M) \implies$
 $\text{conflicting } (\text{cons-trail } M \text{ st}) = \text{conflicting } st \text{ and}$
conflicting-tl-trail[simp]:
 $\bigwedge st. \text{conflicting } (\text{tl-trail } st) = \text{conflicting } st \text{ and}$
conflicting-add-init-cls[simp]:
 $\bigwedge st \text{ C. no-dup } (\text{trail } st) \implies \text{conflicting } (\text{add-init-cls } C \text{ st}) = \text{conflicting } st \text{ and}$
conflicting-add-learned-cls[simp]:
 $\bigwedge C \text{ st. no-dup } (\text{trail } st) \implies \text{conflicting } (\text{add-learned-cls } C \text{ st}) = \text{conflicting } st \text{ and}$
conflicting-remove-cls[simp]:
 $\bigwedge C \text{ st. conflicting } (\text{remove-cls } C \text{ st}) = \text{conflicting } st \text{ and}$
conflicting-update-backtrack-lvl[simp]:
 $\bigwedge st \text{ C. conflicting } (\text{update-backtrack-lvl } C \text{ st}) = \text{conflicting } st \text{ and}$
conflicting-update-conflicting[simp]:
 $\bigwedge C \text{ st. conflicting } (\text{update-conflicting } C \text{ st}) = C \text{ and}$

init-state-trail[simp]: $\bigwedge N. \text{trail } (\text{init-state } N) = [] \text{ and}$
init-state-clss[simp]: $\bigwedge N. \text{init-clss } (\text{init-state } N) = N \text{ and}$
init-state-learned-clss[simp]: $\bigwedge N. \text{learned-clss } (\text{init-state } N) = \{\#\} \text{ and}$
init-state-backtrack-lvl[simp]: $\bigwedge N. \text{backtrack-lvl } (\text{init-state } N) = 0 \text{ and}$
init-state-conflicting[simp]: $\bigwedge N. \text{conflicting } (\text{init-state } N) = \text{None} \text{ and}$

trail-restart-state[simp]: $\text{trail } (\text{restart-state } S) = [] \text{ and}$
init-clss-restart-state[simp]: $\text{init-clss } (\text{restart-state } S) = \text{init-clss } S \text{ and}$
learned-clss-restart-state[intro]: $\text{learned-clss } (\text{restart-state } S) \subseteq\# \text{learned-clss } S \text{ and}$
backtrack-lvl-restart-state[simp]: $\text{backtrack-lvl } (\text{restart-state } S) = 0 \text{ and}$
conflicting-restart-state[simp]: $\text{conflicting } (\text{restart-state } S) = \text{None}$

begin

definition $clauses :: 'st \Rightarrow 'v\ clauses$ **where**
 $clauses\ S = init-clss\ S + learned-clss\ S$

lemma

shows

$clauses-cons-trail[simp]:$

$undefined-lit\ (trail\ S)\ (lit-of\ M) \Longrightarrow clauses\ (cons-trail\ M\ S) = clauses\ S$ **and**

$clss-tl-trail[simp]: clauses\ (tl-trail\ S) = clauses\ S$ **and**

$clauses-add-learned-clss-unfolded:$

$no-dup\ (trail\ S) \Longrightarrow clauses\ (add-learned-clss\ U\ S) = \{\#U\# \} + learned-clss\ S + init-clss\ S$
and

$clauses-add-init-clss[simp]:$

$no-dup\ (trail\ S) \Longrightarrow clauses\ (add-init-clss\ N\ S) = \{\#N\# \} + init-clss\ S + learned-clss\ S$ **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**

$clauses-remove-clss[simp]:$

$clauses\ (remove-clss\ C\ S) = clauses\ S - replicate-mset\ (count\ (clauses\ S)\ C)\ C$ **and**

$clauses-add-learned-clss[simp]:$

$no-dup\ (trail\ S) \Longrightarrow clauses\ (add-learned-clss\ C\ S) = \{\#C\# \} + clauses\ S$ **and**

$clauses-restart[simp]: clauses\ (restart-state\ S) \subseteq \# clauses\ S$ **and**

$clauses-init-state[simp]: \bigwedge N. clauses\ (init-state\ N) = N$

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 $state :: 'st \Rightarrow ('v, nat, 'v\ clause)\ marked-lit\ list \times 'v\ clauses \times 'v\ clauses$
 $\times nat \times 'v\ clause\ option$ **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* ~ 50) **where**
 $S \sim T \iff state\ S = state\ T$

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 $state-eq-trans:$

$S \sim T \Longrightarrow T \sim U \Longrightarrow S \sim U$

unfolding $state-eq-def$ **by** *auto*

lemma

shows

$state-eq-trail: S \sim T \Longrightarrow trail\ S = trail\ T$ **and**

$state-eq-init-clss: S \sim T \Longrightarrow init-clss\ S = init-clss\ T$ **and**

$state-eq-learned-clss: S \sim T \Longrightarrow learned-clss\ S = learned-clss\ T$ **and**

$state-eq-backtrack-lvl: S \sim T \Longrightarrow backtrack-lvl\ S = backtrack-lvl\ T$ **and**

$state-eq-conflicting: S \sim T \Longrightarrow conflicting\ S = conflicting\ T$ **and**

$state-eq-clauses: S \sim T \Longrightarrow clauses\ S = clauses\ T$ **and**

state-eq-undefined-lit: $S \sim T \implies \text{undefined-lit } (\text{trail } S) \text{ } L = \text{undefined-lit } (\text{trail } T) \text{ } L$
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* :: 'a list \Rightarrow 'st \Rightarrow 'st **where**
reduce-trail-to $F \ S =$
 (if $\text{length } (\text{trail } S) = \text{length } F \vee \text{trail } S = []$ then S else *reduce-trail-to* $F \ (\text{tl-trail } S)$)
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* $[]$: ($'v, \text{nat}, 'v$ *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*:
 $\text{clauses } (\text{reduce-trail-to } [] \ S) = \text{clauses } S$
proof (*induction* $[] \ S$ *rule: reduce-trail-to.induct*)
case ($1 \ Sa$)
then have $\text{clauses } (\text{reduce-trail-to } ([]::'a \text{ list}) \ (\text{tl-trail } Sa)) = \text{clauses } (\text{tl-trail } Sa)$
 $\vee \text{trail } Sa = []$
by *fastforce*
then show $\text{clauses } (\text{reduce-trail-to } ([]::'a \text{ list}) \ Sa) = \text{clauses } Sa$
by (*metis (no-types) length-0-conv reduce-trail-to-eq-length clss-tl-trail*
reduce-trail-to-length-ne)

qed

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* *clss-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*]:
 $\text{learned-clss } (\text{reduce-trail-to } F S) = \text{learned-clss } S$
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*:
 $\text{trail } S = \text{trail } T \implies \text{trail } (\text{reduce-trail-to } F S) = \text{trail } (\text{reduce-trail-to } F T)$
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 $\text{reduce-trail-to } F S \sim \text{reduce-trail-to } F T$
proof –
have $\text{trail } (\text{reduce-trail-to } F S) = \text{trail } (\text{reduce-trail-to } F T)$
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*]:
 $\text{trail } S = F' @ \text{Marked } K d \# F \implies (\text{trail } (\text{reduce-trail-to } F S)) = F$
apply (*rule* *reduce-trail-to-skip-beginning*[*of* $- F' @ \text{Marked } K d \# []$])
by (*cases* F') (*auto simp* *add*:*tl-append* *reduce-trail-to-skip-beginning*)

lemma *reduce-trail-to-add-learned-cls*[*simp*]:
 $\text{no-dup } (\text{trail } S) \implies$
 $\text{trail } (\text{reduce-trail-to } F (\text{add-learned-cls } C S)) = \text{trail } (\text{reduce-trail-to } F S)$
by (*rule* *trail-eq-reduce-trail-to-eq*) *auto*

lemma *reduce-trail-to-add-init-cls*[*simp*]:
 $\text{no-dup } (\text{trail } S) \implies$

trail (*reduce-trail-to* *F* (*add-init-cls* *C* *S*)) = *trail* (*reduce-trail-to* *F* *S*)
by (*rule* *trail-eq-reduce-trail-to-eq*) *auto*

lemma *reduce-trail-to-remove-learned-cls*[*simp*]:
trail (*reduce-trail-to* *F* (*remove-cls* *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*) ∈ *set* (*get-all-marked-decomposition* *M*)
shows *a* = [] ∨ (*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*:
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 *init-clss-append-trail*:

no-dup ($M @ \text{trail } S$) $\implies \text{init-clss } (\text{append-trail } M S) = \text{init-clss } S$
by (*induction* M *arbitrary*: S) (*auto simp*: *defined-lit-map*)

lemma *learned-clss-append-trail*:

no-dup ($M @ \text{trail } S$) $\implies \text{learned-clss } (\text{append-trail } M S) = \text{learned-clss } S$
by (*induction* M *arbitrary*: S) (*auto simp*: *defined-lit-map*)

lemma *conflicting-append-trail*:

no-dup ($M @ \text{trail } S$) $\implies \text{conflicting } (\text{append-trail } M S) = \text{conflicting } S$
by (*induction* M *arbitrary*: S) (*auto simp*: *defined-lit-map*)

lemma *backtrack-lvl-append-trail*:

no-dup ($M @ \text{trail } S$) $\implies \text{backtrack-lvl } (\text{append-trail } M S) = \text{backtrack-lvl } S$
by (*induction* M *arbitrary*: S) (*auto simp*: *defined-lit-map*)

lemma *clauses-append-trail*:

no-dup ($M @ \text{trail } S$) $\implies \text{clauses } (\text{append-trail } M S) = \text{clauses } S$
by (*induction* M *arbitrary*: S) (*auto simp*: *defined-lit-map*)

lemmas *state-access-simp* =

trail-append-trail init-clss-append-trail learned-clss-append-trail backtrack-lvl-append-trail
clauses-append-trail conflicting-append-trail

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 $M S = \text{append-trail } (\text{rev } M) (\text{reduce-trail-to } ([:: 'v \text{ list}]) S)$

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

cdcl_W =
state_W *trail init-clss learned-clss backtrack-lvl conflicting cons-trail tl-trail add-init-cl*
add-learned-cl *remove-cl* *update-backtrack-lvl update-conflicting init-state*
restart-state

for

trail :: $'st \Rightarrow ('v, \text{nat}, 'v \text{ clause}) \text{ marked-lits}$ **and**
init-clss :: $'st \Rightarrow 'v \text{ clauses}$ **and**
learned-clss :: $'st \Rightarrow 'v \text{ clauses}$ **and**
backtrack-lvl :: $'st \Rightarrow \text{nat}$ **and**
conflicting :: $'st \Rightarrow 'v \text{ clause option}$ **and**

cons-trail :: $('v, \text{nat}, 'v \text{ clause}) \text{ marked-lit} \Rightarrow 'st \Rightarrow 'st$ **and**
tl-trail :: $'st \Rightarrow 'st$ **and**
add-init-cl :: $'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$ **and**
add-learned-cl :: $'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$ **and**
remove-cl :: $'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$ **and**
update-backtrack-lvl :: $\text{nat} \Rightarrow 'st \Rightarrow 'st$ **and**

```

update-conflicting :: 'v clause option  $\Rightarrow$  '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  $S = (M, N, U, k, \text{None}) \Rightarrow C + \{\#L\# \} \in \# \text{ clauses } S \Rightarrow M \models_{as} C \text{Not } C$ 
 $\Rightarrow \text{undefined-lit } (\text{trail } S) L$ 
 $\Rightarrow T \sim \text{cons-trail } (\text{Propagated } L (C + \{\#L\# \})) S$ 
 $\Rightarrow \text{propagate } S T$ 
inductive-cases propagateE[elim]: propagate  $S T$ 
thm propagateE

inductive conflict :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
conflict-rule[intro]: state  $S = (M, N, U, k, \text{None}) \Rightarrow D \in \# \text{ clauses } S \Rightarrow M \models_{as} C \text{Not } D$ 
 $\Rightarrow T \sim \text{update-conflicting } (\text{Some } D) S$ 
 $\Rightarrow \text{conflict } S T$ 

inductive-cases conflictE[elim]: conflict  $S S'$ 

inductive backtrack :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
backtrack-rule[intro]: state  $S = (M, N, U, k, \text{Some } (D + \{\#L\# \}))$ 
 $\Rightarrow (\text{Marked } K (i+1) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } M)$ 
 $\Rightarrow \text{get-level } M L = k$ 
 $\Rightarrow \text{get-level } M L = \text{get-maximum-level } M (D + \{\#L\# \})$ 
 $\Rightarrow \text{get-maximum-level } M D = i$ 
 $\Rightarrow T \sim \text{cons-trail } (\text{Propagated } L (D + \{\#L\# \}))$ 
  (reduce-trail-to  $M1$ 
    (add-learned-cls  $(D + \{\#L\# \})$ 
      (update-backtrack-lvl  $i$ 
        (update-conflicting  $\text{None } S$ ))))
 $\Rightarrow \text{backtrack } S T$ 
inductive-cases backtrackE[elim]: backtrack  $S S'$ 
thm backtrackE

inductive decide :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
decide-rule[intro]: state  $S = (M, N, U, k, \text{None})$ 
 $\Rightarrow \text{undefined-lit } M L \Rightarrow \text{atm-of } L \in \text{atms-of-msu } (\text{init-clss } S)$ 
 $\Rightarrow T \sim \text{cons-trail } (\text{Marked } L (k+1)) (\text{incr-lvl } S)$ 
 $\Rightarrow \text{decide } S T$ 
inductive-cases decideE[elim]: decide  $S S'$ 
thm decideE

inductive skip :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
skip-rule[intro]: state  $S = (\text{Propagated } L C' \# M, N, U, k, \text{Some } D) \Rightarrow -L \notin \# D \Rightarrow D \neq \{\#\}$ 
 $\Rightarrow T \sim \text{tl-trail } S$ 
 $\Rightarrow \text{skip } S T$ 
inductive-cases skipE[elim]: skip  $S S'$ 
thm skipE

get-maximum-level  $(\text{Propagated } L (C + \{\#L\# \}) \# M) D = k \vee k = 0$  is equivalent to
get-maximum-level  $(\text{Propagated } L (C + \{\#L\# \}) \# M) D = k$ 

inductive resolve :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where

```

resolve-rule[intro]:
 state $S = (\text{Propagated } L (C + \{\#L\#\}) \# M, N, U, k, \text{Some } (D + \{\#-L\#\}))$
 $\implies \text{get-maximum-level } (\text{Propagated } L (C + \{\#L\#\}) \# M) D = k$
 $\implies T \sim \text{update-conflicting } (\text{Some } (D \# \cup C)) (\text{tl-trail } S)$
 $\implies \text{resolve } S T$

inductive-cases *resolveE*[elim]: *resolve* $S S'$

thm *resolveE*

inductive *restart* :: '*st* \Rightarrow '*st* \Rightarrow bool **where**

restart: state $S = (M, N, U, k, \text{None}) \implies \neg M \models_{\text{asm}} \text{clauses } S$

$\implies T \sim \text{restart-state } S$

$\implies \text{restart } S T$

inductive-cases *restartE*[elim]: *restart* $S T$

thm *restartE*

We add the condition $C \notin \# \text{init-clss } S$, to maintain consistency even without the strategy.

inductive *forget* :: '*st* \Rightarrow '*st* \Rightarrow bool **where**

forget-rule: state $S = (M, N, \{\#C\#\} + U, k, \text{None})$

$\implies \neg M \models_{\text{asm}} \text{clauses } S$

$\implies C \notin \text{set } (\text{get-all-mark-of-propagated } (\text{trail } S))$

$\implies C \notin \# \text{init-clss } S$

$\implies C \in \# \text{learned-clss } S$

$\implies T \sim \text{remove-cl } C S$

$\implies \text{forget } S T$

inductive-cases *forgetE*[elim]: *forget* $S T$

inductive *cdcl_W-rf* :: '*st* \Rightarrow '*st* \Rightarrow bool **for** $S :: 'st$ **where**

restart: *restart* $S T \implies \text{cdcl}_W\text{-rf } S T$ |

forget: *forget* $S T \implies \text{cdcl}_W\text{-rf } S T$

inductive *cdcl_W-bj* :: '*st* \Rightarrow '*st* \Rightarrow bool **where**

skip[intro]: *skip* $S S' \implies \text{cdcl}_W\text{-bj } S S'$ |

resolve[intro]: *resolve* $S S' \implies \text{cdcl}_W\text{-bj } S S'$ |

backtrack[intro]: *backtrack* $S S' \implies \text{cdcl}_W\text{-bj } S S'$

inductive-cases *cdcl_W-bjE*: *cdcl_W-bj* $S T$

inductive *cdcl_W-o*: '*st* \Rightarrow '*st* \Rightarrow bool **for** $S :: 'st$ **where**

decide[intro]: *decide* $S S' \implies \text{cdcl}_W\text{-o } S S'$ |

bj[intro]: *cdcl_W-bj* $S S' \implies \text{cdcl}_W\text{-o } S S'$

inductive *cdcl_W* :: '*st* \Rightarrow '*st* \Rightarrow bool **for** $S :: 'st$ **where**

propagate: *propagate* $S S' \implies \text{cdcl}_W S S'$ |

conflict: *conflict* $S S' \implies \text{cdcl}_W S S'$ |

other: *cdcl_W-o* $S S' \implies \text{cdcl}_W S S'$ |

rf: *cdcl_W-rf* $S S' \implies \text{cdcl}_W S S'$

lemma *rtrancp-propagate-is-rtrancp-cdcl_W*:

*propagate*** $S S' \implies \text{cdcl}_W^{**} S S'$

by (*induction rule*: *rtrancp-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

```

cdclW: cdclW S S' and
propagate:  $\bigwedge T. \text{propagate } S \ T \implies P \ S \ T$  and
conflict:  $\bigwedge T. \text{conflict } S \ T \implies P \ S \ T$  and
forget:  $\bigwedge T. \text{forget } S \ T \implies P \ S \ T$  and
restart:  $\bigwedge T. \text{restart } S \ T \implies P \ S \ T$  and
decide:  $\bigwedge T. \text{decide } S \ T \implies P \ S \ T$  and
skip:  $\bigwedge T. \text{skip } S \ T \implies P \ S \ T$  and
resolve:  $\bigwedge T. \text{resolve } S \ T \implies P \ S \ T$  and
backtrack:  $\bigwedge T. \text{backtrack } S \ T \implies P \ S \ T$ 
shows P S S'
using assms(1)
proof (induct S' rule: cdclW.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: cdclW-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: cdclW-bj.induct) auto
    qed
  next
  case (rf S')
  then show ?case
    by (induct rule: cdclW-rf.induct) (fast dest: forget restart)+
  qed
qed

lemma cdclW-all-induct[consumes 1, case-names propagate conflict forget restart decide skip
  resolve backtrack]:
fixes S :: 'st
assumes
cdclW: cdclW S S' and
propagateH:  $\bigwedge C \ L \ T. C + \{\#L\# \} \in \# \text{ clauses } S \implies \text{trail } S \models_{as} C \text{Not } C$ 
 $\implies \text{undefined-lit } (\text{trail } S) \ L \implies \text{conflicting } S = \text{None}$ 
 $\implies T \sim \text{cons-trail } (\text{Propagated } L \ (C + \{\#L\# \})) \ S$ 
 $\implies P \ S \ T$  and
conflictH:  $\bigwedge D \ T. D \in \# \text{ clauses } S \implies \text{conflicting } S = \text{None} \implies \text{trail } S \models_{as} C \text{Not } D$ 
 $\implies T \sim \text{update-conflicting } (\text{Some } D) \ S$ 
 $\implies P \ S \ T$  and
forgetH:  $\bigwedge C \ T. \neg \text{trail } S \models_{asm} \text{clauses } S$ 
 $\implies C \notin \text{set } (\text{get-all-mark-of-propagated } (\text{trail } S))$ 
 $\implies C \notin \# \text{ init-clss } S$ 
 $\implies C \in \# \text{ learned-clss } S$ 
 $\implies \text{conflicting } S = \text{None}$ 
 $\implies T \sim \text{remove-cls } C \ S$ 
 $\implies P \ S \ T$  and
restartH:  $\bigwedge T. \neg \text{trail } S \models_{asm} \text{clauses } S$ 
 $\implies \text{conflicting } S = \text{None}$ 
 $\implies T \sim \text{restart-state } S$ 

```

```

     $\Rightarrow P S T$  and
  decideH:  $\bigwedge L T. \text{conflicting } S = \text{None} \Rightarrow \text{undefined-lit } (\text{trail } S) L$ 
     $\Rightarrow \text{atm-of } L \in \text{atms-of-msu } (\text{init-clss } S)$ 
     $\Rightarrow T \sim \text{cons-trail } (\text{Marked } L (\text{backtrack-lvl } S + 1)) (\text{incr-lvl } S)$ 
     $\Rightarrow P S T$  and
  skipH:  $\bigwedge L C' M D T. \text{trail } S = \text{Propagated } L C' \# M$ 
     $\Rightarrow \text{conflicting } S = \text{Some } D \Rightarrow -L \notin \# D \Rightarrow D \neq \{\#\}$ 
     $\Rightarrow T \sim \text{tl-trail } S$ 
     $\Rightarrow P S T$  and
  resolveH:  $\bigwedge L C M D T.$ 
     $\text{trail } S = \text{Propagated } L ( (C + \{\#L\# \}) \# M$ 
     $\Rightarrow \text{conflicting } S = \text{Some } (D + \{\#-L\# \})$ 
     $\Rightarrow \text{get-maximum-level } (\text{Propagated } L (C + \{\#L\# \}) \# M) D = \text{backtrack-lvl } S$ 
     $\Rightarrow T \sim (\text{update-conflicting } (\text{Some } (D \# \cup C)) (\text{tl-trail } S))$ 
     $\Rightarrow P S T$  and
  backtrackH:  $\bigwedge K i M1 M2 L D T.$ 
     $(\text{Marked } K (\text{Suc } i) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$ 
     $\Rightarrow \text{get-level } (\text{trail } S) L = \text{backtrack-lvl } S$ 
     $\Rightarrow \text{conflicting } S = \text{Some } (D + \{\#L\# \})$ 
     $\Rightarrow \text{get-maximum-level } (\text{trail } S) (D + \{\#L\# \}) = \text{get-level } (\text{trail } S) L$ 
     $\Rightarrow \text{get-maximum-level } (\text{trail } S) D \equiv i$ 
     $\Rightarrow T \sim \text{cons-trail } (\text{Propagated } L (D + \{\#L\# \}))$ 
      (reduce-trail-to M1
      (add-learned-cls (D + {\#L\#}))
      (update-backtrack-lvl i
      (update-conflicting None S))))
     $\Rightarrow P S T$ 
  shows  $P S S'$ 
  using cdclW
  proof (induct  $S S'$  rule: cdclW-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 . *conflicting* $S = None \implies undefined-lit$ (*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)
 $\implies P$ S T **and**
 $skipH$: $\bigwedge L$ $C' M D T$. *trail* $S = Propagated$ L $C' \# M$
 $\implies conflicting$ $S = Some$ $D \implies -L \notin \# D \implies D \neq \{\#\}$
 $\implies T \sim tl-trail$ S
 $\implies P$ S T **and**
 $resolveH$: $\bigwedge L$ $C M D T$.
 $trail$ $S = Propagated$ L ($(C + \{\#L\# \}) \# M$)
 $\implies conflicting$ $S = Some$ ($D + \{\#-L\# \}$)
 $\implies get-maximum-level$ (*Propagated* L ($C + \{\#L\# \}) \# M$) $D = backtrack-lvl$ S
 $\implies T \sim update-conflicting$ (*Some* ($D \# \cup C$)) (*tl-trail* S)
 $\implies P$ S T **and**
 $backtrackH$: $\bigwedge K$ $i M1 M2 L D T$.
(*Marked* K (*Suc* i) $\# M1, M2$) $\in set$ (*get-all-marked-decomposition* (*trail* S))
 $\implies get-level$ (*trail* S) $L = backtrack-lvl$ S
 $\implies conflicting$ $S = Some$ ($D + \{\#L\# \}$)
 $\implies get-level$ (*trail* S) $L = get-maximum-level$ (*trail* S) ($D + \{\#L\# \}$)
 $\implies get-maximum-level$ (*trail* S) $D \equiv i$
 $\implies T \sim cons-trail$ (*Propagated* L ($D + \{\#L\# \}$))
(*reduce-trail-to* $M1$
(*add-learned-cls* ($D + \{\#L\# \}$)
(*update-backtrack-lvl* i
(*update-conflicting* *None* S))))
 $\implies P$ S T
shows P S T
using *cdcl_W* **apply** (*induct* T *rule*: *cdcl_W-o.induct*)
using *assms*(2) **apply** *auto*[1]
apply (*elim* *cdcl_W-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 *cdcl_W-o.induct*

lemma *cdcl_W-o-all-rules-induct*[consumes 1, case-names decide backtrack skip resolve]:

fixes $S T :: 'st$

assumes

cdcl_W-o S T **and**

$\bigwedge T$. *decide* S $T \implies P$ S T **and**

$\bigwedge T$. *backtrack* S $T \implies P$ S T **and**

$\bigwedge T$. *skip* S $T \implies P$ S T **and**

$\bigwedge T$. *resolve* S $T \implies P$ S T

shows P S T

using *assms* **by** (*induct* T *rule*: *cdcl_W-o.induct*) (*auto* *simp*: *cdcl_W-bj.simps*)

lemma *cdcl_W-o-rule-cases*[consumes 1, case-names decide backtrack skip resolve]:

fixes $S T :: 'st$

assumes

cdcl_W-o S T **and**

decide S $T \implies P$ **and**

$\text{backtrack } S \ T \implies P$ **and**
 $\text{skip } S \ T \implies P$ **and**
 $\text{resolve } S \ T \implies P$
shows P
using *assms* **by** (*auto simp: cdcl_W-o.simps cdcl_W-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 : $\text{get-level } (\text{trail } S) \ L = \text{backtrack-lvl } S$
and $M1$: $(\text{Marked } K \ (i + 1) \ \# \ M1, \ M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$
and *no-dup*: $\text{no-dup } (\text{trail } S)$
and *bt-l*: $\text{backtrack-lvl } S = \text{length } (\text{get-all-levels-of-marked } (\text{trail } S))$
and *order*: $\text{get-all-levels-of-marked } (\text{trail } S) = \text{rev } ([1..<(1+\text{length } (\text{get-all-levels-of-marked } (\text{trail } S)))])$
shows $\text{atm-of } L \notin \text{atm-of ' lits-of } M1$

proof

let $?M = \text{trail } S$
assume $L\text{-in-}M1$: $\text{atm-of } L \in \text{atm-of ' lits-of } M1$
obtain c **where** Mc : $\text{trail } S = c \ @ \ M2 \ @ \ \text{Marked } K \ (i + 1) \ \# \ M1$ **using** $M1$ **by** *blast*
have $\text{atm-of } L \notin \text{atm-of ' lits-of } c$
using $L\text{-in-}M1$ *no-dup mk-disjoint-insert unfolding Mc lits-of-def* **by** *force*
have $g\text{-}M\text{-eq-}g\text{-}M1$: $\text{get-level } ?M \ L = \text{get-level } M1 \ L$
using $L\text{-in-}M1$ *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 $\text{get-level } M1 \ L < \text{Suc } i$
using $\text{get-rev-level-less-max-get-all-levels-of-marked}[of \ \text{rev } M1 \ 0 \ L]$ **by** *linarith*
moreover have $\text{Suc } i \leq \text{backtrack-lvl } S$ **using** *bt-l* **by** (*simp add: Mc g*)
ultimately show *False* **using** $L \ g\text{-}M\text{-eq-}g\text{-}M1$ **by** *auto*

qed

lemma *cdcl_W-distinctinv-1*:

assumes
 $\text{cdcl}_W \ S \ S'$ **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 (*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** $n\text{-}d = \text{this}(7)$
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 $Mc \ n\text{-}d$ **by** *fastforce*
moreover have $\text{atm-of } L \notin (\lambda l. \text{atm-of } (\text{lit-of } l)) \ \text{' set } M1$

using *backtrack-lit-skipped*[*of S L K i M1 M2*] *L decomp backtrack.prem*s
by (*fastforce simp: lits-of-def*)
moreover then have *undefined-lit M1 L*
by (*simp add: defined-lit-map*)
ultimately show *?case using decomp T n-d by simp*
qed (*auto simp: defined-lit-map*)

lemma *cdcl_W-consistent-inv-2*:

assumes
cdcl_W S S' **and**
no-dup (trail S) **and**
backtrack-lvl S = length (get-all-levels-of-marked (trail S)) **and**
get-all-levels-of-marked (trail S) = rev [1.. $1 + \text{length (get-all-levels-of-marked (trail S))}$]]
shows *consistent-interp (lits-of (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**
backtrack-lvl S = length (get-all-levels-of-marked (trail S)) **and**
get-all-levels-of-marked (trail S) =
rev ([1.. $1 + \text{length (get-all-levels-of-marked (trail S))}$]]) **and**
n-d[simp]: no-dup (trail S)
shows *backtrack-lvl S' = length (get-all-levels-of-marked (trail S'))*
using *assms*

proof (*induct rule: cdcl_W-o-induct*)

case (*backtrack K i M1 M2 L D T*) **note** *decomp = this(1)* **and** *T = this(6)* **and** *level = 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.. $1 + (\text{length (get-all-levels-of-marked (trail S))})$]]
using *level* **by** (*auto simp: rev-swap[symmetric]*)
moreover have *atm-of L \notin ($\lambda l. \text{atm-of (lit-of l)}$) ‘set M1*
using *backtrack-lit-skipped*[*of S L 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 *cdcl_W-rf-bt*:

assumes
cdcl_W-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.. $1 + \text{length (get-all-levels-of-marked (trail S))}$]]
shows *backtrack-lvl S' = length (get-all-levels-of-marked (trail S'))*
using *assms* **by** (*induct rule: cdcl_W-rf.induct*) *auto*

lemma *cdcl_W-bt*:

assumes
cdcl_W S S' **and**

```

    backtrack-lvl S = length (get-all-levels-of-marked (trail S)) and
    get-all-levels-of-marked (trail S)
    = rev ([1..<(1+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..<(1+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..<(1+length (get-all-levels-of-marked (trail S')))])
  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.. $<1 + \text{length (get-all-levels-of-marked ?M)}$ ]
    using decide.prem by simp
  have k: ?k = length (get-all-levels-of-marked ?M)
    using decide.prem 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.. $<1 + \text{length (get-all-levels-of-marked ?M)}$ ]
    using H by auto
  moreover have ... = rev [Suc 0.. $< \text{Suc (1 + length (get-all-levels-of-marked ?M))}$ ]
    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 confl = this(2) and T = this(6)
  and
    all-marked = this(8) and bt-lvl = this(7)
  have atm-of L  $\notin (\lambda l. \text{atm-of (lit-of l)})$  ' set M1
    using backtrack-lit-skipped[of S L 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.. $<2 + \text{length (get-all-levels-of-marked c)} + (\text{length (get-all-levels-of-marked M2)} + \text{length (get-all-levels-of-marked M1)})$ ]
    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 $1 + \text{length (get-all-levels-of-marked (trail S))}$ instead of $\text{backtrack-lvl } S$ 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* $S = \text{length } (\text{get-all-levels-of-marked } (\text{trail } S))$
 \wedge *get-all-levels-of-marked* (*trail* S)
 $= \text{rev } ([1..<1 + \text{length } (\text{get-all-levels-of-marked } (\text{trail } S))])$

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 $rtranclp$ - $cdcl_W$ -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: rtranclp-induct*)
(*auto intro: cdcl_W-consistent-inv*)

lemma $tranclp$ - $cdcl_W$ -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: tranclp-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* (*trail* S) $L \leq \text{backtrack-lvl } S$

proof –

have $\text{get-all-levels-of-marked } (\text{trail } S) = \text{rev } [1..<1 + \text{backtrack-lvl } S]$
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 rev (trail S) 0 L*]
by (*auto simp: Max-n-upt*)

qed

lemma *backtrack-ex-decomp*:

assumes M -l: $cdcl_W$ - M -level-inv S
and i -S: $i < \text{backtrack-lvl } S$
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 $?M = \text{trail } S$

have

g : $\text{get-all-levels-of-marked } (\text{trail } S) = \text{rev } [\text{Suc } 0..<\text{Suc } (\text{backtrack-lvl } S)]$

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 $\text{tr-}S$: $\text{trail } S = c @ \text{Marked } K \ (i + 1) \ \# \ c'$

using $\text{in-get-all-levels-of-marked-iff-decomp}$ [of $i+1 \ \text{trail } S$] 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 $\text{tr-}S$ apply (induct c rule: $\text{marked-lit-list-induct}$)

apply $\text{auto}[2]$

apply (rename-tac $L \ m \ xs$,

$\text{case-tac } hd \ (\text{get-all-marked-decomposition } (xs @ \text{Marked } K \ (\text{Suc } i) \ \# \ c'))$)

apply (case-tac $\text{get-all-marked-decomposition } (xs @ \text{Marked } K \ (\text{Suc } i) \ \# \ c')$)

by auto

then show $?thesis$ by blast

qed

17.4.2 Better-Suited Induction Principle

We 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 $\text{backtrack-induction-lev}$ [consumes 1, case-names M -devel-inv *backtrack*]:

assumes

bt : $\text{backtrack } S \ T$ **and**

inv : cdcl_W - M -level-inv S **and**

backtrackH : $\bigwedge K \ i \ M1 \ M2 \ L \ D \ T.$

$(\text{Marked } K \ (\text{Suc } i) \ \# \ M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$

$\implies \text{get-level } (\text{trail } S) \ L = \text{backtrack-lvl } S$

$\implies \text{conflicting } S = \text{Some } (D + \{\#L\# \})$

$\implies \text{get-level } (\text{trail } S) \ L = \text{get-maximum-level } (\text{trail } S) \ (D + \{\#L\# \})$

$\implies \text{get-maximum-level } (\text{trail } S) \ D \equiv i$

$\implies \text{undefined-lit } M1 \ L$

$\implies T \sim \text{cons-trail } (\text{Propagated } L \ (D + \{\#L\# \}))$

($\text{reduce-trail-to } M1$

($\text{add-learned-cls } (D + \{\#L\# \})$

($\text{update-backtrack-lvl } i$

($\text{update-conflicting } \text{None } S$))))

$\implies P \ S \ T$

shows $P \ S \ T$

proof –

obtain $K \ i \ M1 \ M2 \ L \ D$ **where**

decomp : $(\text{Marked } K \ (\text{Suc } i) \ \# \ M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$ **and**

L : $\text{get-level } (\text{trail } S) \ L = \text{backtrack-lvl } S$ **and**

confl : $\text{conflicting } S = \text{Some } (D + \{\#L\# \})$ **and**

lev-L : $\text{get-level } (\text{trail } S) \ L = \text{get-maximum-level } (\text{trail } S) \ (D + \{\#L\# \})$ **and**

lev-D : $\text{get-maximum-level } (\text{trail } S) \ D \equiv i$ **and**

T : $T \sim \text{cons-trail } (\text{Propagated } L \ (D + \{\#L\# \}))$

($\text{reduce-trail-to } M1$

($\text{add-learned-cls } (D + \{\#L\# \})$

($\text{update-backtrack-lvl } i$

```

      (update-conflicting None S))))
using bt by (elim backtrackE) metis

have atm-of L  $\notin$  ( $\lambda l$ . atm-of (lit-of l)) ‘ set M1
  using backtrack-lit-skipped[of S L K i M1 M2] L decomp bt confl lev-L lev-D inv
  unfolding cdclW-M-level-inv-def
  by (fastforce simp add: lits-of-def)
then have undefined-lit M1 L
  by (auto simp: defined-lit-map)
then show ?thesis
  using backtrackH[OF decomp L confl lev-L lev-D - T] by simp
qed

lemmas backtrack-induction-lev2 = backtrack-induction-lev[consumes 2, case-names backtrack]

lemma cdclW-all-induct-lev-full:
  fixes S :: 'st
  assumes
    cdclW: cdclW S S' and
    inv[simp]: cdclW-M-level-inv S and
    propagateH:  $\bigwedge C L T$ .  $C + \{\#L\# \} \in \# \text{ clauses } S \implies \text{trail } S \models_{as} C \text{Not } C$ 
       $\implies \text{undefined-lit } (\text{trail } S) L \implies \text{conflicting } S = \text{None}$ 
       $\implies T \sim \text{cons-trail } (\text{Propagated } L (C + \{\#L\# \})) S$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    conflictH:  $\bigwedge D T$ .  $D \in \# \text{ clauses } S \implies \text{conflicting } S = \text{None} \implies \text{trail } S \models_{as} C \text{Not } D$ 
       $\implies T \sim \text{update-conflicting } (\text{Some } D) S$ 
       $\implies P S T$  and
    forgetH:  $\bigwedge C T$ .  $\neg \text{trail } S \models_{asm} \text{clauses } S$ 
       $\implies C \notin \text{set } (\text{get-all-mark-of-propagated } (\text{trail } S))$ 
       $\implies C \notin \# \text{ init-clss } S$ 
       $\implies C \in \# \text{ learned-clss } S$ 
       $\implies \text{conflicting } S = \text{None}$ 
       $\implies T \sim \text{remove-cl } C S$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    restartH:  $\bigwedge T$ .  $\neg \text{trail } S \models_{asm} \text{clauses } S$ 
       $\implies \text{conflicting } S = \text{None}$ 
       $\implies T \sim \text{restart-state } S$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    decideH:  $\bigwedge L T$ .  $\text{conflicting } S = \text{None} \implies \text{undefined-lit } (\text{trail } S) L$ 
       $\implies \text{atm-of } L \in \text{atms-of-msu } (\text{init-clss } S)$ 
       $\implies T \sim \text{cons-trail } (\text{Marked } L (\text{backtrack-lvl } S + 1)) (\text{incr-lvl } S)$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    skipH:  $\bigwedge L C' M D T$ .  $\text{trail } S = \text{Propagated } L C' \# M$ 
       $\implies \text{conflicting } S = \text{Some } D \implies -L \notin \# D \implies D \neq \{\#\}$ 
       $\implies T \sim \text{tl-trail } S$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    resolveH:  $\bigwedge L C M D T$ .
       $\text{trail } S = \text{Propagated } L ( (C + \{\#L\# \}) \# M$ 
       $\implies \text{conflicting } S = \text{Some } (D + \{\#-L\# \})$ 
       $\implies \text{get-maximum-level } (\text{Propagated } L (C + \{\#L\# \}) \# M) D = \text{backtrack-lvl } S$ 

```

```

    ⇒  $T \sim (\text{update-conflicting } (\text{Some } (D \# \cup C)) (\text{tl-trail } S))$ 
    ⇒  $\text{cdcl}_W\text{-M-level-inv } S$ 
    ⇒  $P \ S \ T$  and
backtrackH:  $\bigwedge K \ i \ M1 \ M2 \ L \ D \ T.$ 
  ( $\text{Marked } K \ (\text{Suc } i) \ \# \ M1, \ M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$ 
  ⇒  $\text{get-level } (\text{trail } S) \ L = \text{backtrack-lvl } S$ 
  ⇒  $\text{conflicting } S = \text{Some } (D + \{\#L\# \})$ 
  ⇒  $\text{get-maximum-level } (\text{trail } S) \ (D + \{\#L\# \}) = \text{get-level } (\text{trail } S) \ L$ 
  ⇒  $\text{get-maximum-level } (\text{trail } S) \ D \equiv i$ 
  ⇒  $\text{undefined-lit } M1 \ L$ 
  ⇒  $T \sim \text{cons-trail } (\text{Propagated } L \ (D + \{\#L\# \}))$ 
    ( $\text{reduce-trail-to } M1$ 
      ( $\text{add-learned-cls } (D + \{\#L\# \})$ 
        ( $\text{update-backtrack-lvl } i$ 
          ( $\text{update-conflicting } \text{None } S))))$ 
  ⇒  $\text{cdcl}_W\text{-M-level-inv } S$ 
  ⇒  $P \ S \ T$ 
shows  $P \ S \ S'$ 
using  $\text{cdcl}_W$ 
proof ( $\text{induct } S' \text{ rule: } \text{cdcl}_W\text{-all-rules-induct}$ )
  case ( $\text{propagate } S'$ )
    then show ?case by ( $\text{elim propagateE}$ ) ( $\text{frule propagateH; simp}$ )
  next
    case ( $\text{conflict } S'$ )
      then show ?case by ( $\text{elim conflictE}$ ) ( $\text{frule conflictH; simp}$ )
  next
    case ( $\text{restart } S'$ )
      then show ?case by ( $\text{elim restartE}$ ) ( $\text{frule restartH; simp}$ )
  next
    case ( $\text{decide } T$ )
      then show ?case by ( $\text{elim decideE}$ ) ( $\text{frule decideH; simp}$ )
  next
    case ( $\text{backtrack } S'$ )
      then show ?case
        apply ( $\text{induction rule: backtrack-induction-lev}$ )
        apply ( $\text{rule inv}$ )
        by ( $\text{rule backtrackH;}$ 
           $\text{fastforce simp del: state-simp simp add: state-eq-def dest!: HOL.meta-eq-to-obj-eq}$ )
  next
    case ( $\text{forget } S'$ )
      then show ?case using  $\text{forgetH}$  by  $\text{auto}$ 
  next
    case ( $\text{skip } S'$ )
      then show ?case using  $\text{skipH}$  by  $\text{auto}$ 
  next
    case ( $\text{resolve } S'$ )
      then show ?case by ( $\text{elim resolveE}$ ) ( $\text{frule resolveH; simp}$ )
qed

lemmas  $\text{cdcl}_W\text{-all-induct-lev2} = \text{cdcl}_W\text{-all-induct-lev-full}[\text{consumes } 2, \text{ case-names propagate conflict}$ 
 $\text{forget restart decide skip resolve backtrack}]$ 

lemmas  $\text{cdcl}_W\text{-all-induct-lev} = \text{cdcl}_W\text{-all-induct-lev-full}[\text{consumes } 1, \text{ case-names lev-inv propagate}$ 
 $\text{conflict forget restart decide skip resolve backtrack}]$ 

```

```

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:  $\bigwedge L T. \text{conflicting } S = \text{None} \implies \text{undefined-lit } (\text{trail } S) L$ 
       $\implies \text{atm-of } L \in \text{atms-of-msu } (\text{init-clss } S)$ 
       $\implies T \sim \text{cons-trail } (\text{Marked } L (\text{backtrack-lvl } S + 1)) (\text{incr-lvl } S)$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    skipH:  $\bigwedge L C' M D T. \text{trail } S = \text{Propagated } L C' \# M$ 
       $\implies \text{conflicting } S = \text{Some } D \implies -L \notin \# D \implies D \neq \{\#\}$ 
       $\implies T \sim \text{tl-trail } S$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    resolveH:  $\bigwedge L C M D T.$ 
       $\text{trail } S = \text{Propagated } L ( (C + \{\#L\# \}) \# M$ 
       $\implies \text{conflicting } S = \text{Some } (D + \{\#-L\# \})$ 
       $\implies \text{get-maximum-level } (\text{Propagated } L (C + \{\#L\# \}) \# M) D = \text{backtrack-lvl } S$ 
       $\implies T \sim \text{update-conflicting } (\text{Some } (D \# \cup C)) (\text{tl-trail } S)$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$  and
    backtrackH:  $\bigwedge K i M1 M2 L D T.$ 
       $(\text{Marked } K (\text{Suc } i) \# M1, M2) \in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$ 
       $\implies \text{get-level } (\text{trail } S) L = \text{backtrack-lvl } S$ 
       $\implies \text{conflicting } S = \text{Some } (D + \{\#L\# \})$ 
       $\implies \text{get-level } (\text{trail } S) L = \text{get-maximum-level } (\text{trail } S) (D + \{\#L\# \})$ 
       $\implies \text{get-maximum-level } (\text{trail } S) D \equiv i$ 
       $\implies \text{undefined-lit } M1 L$ 
       $\implies T \sim \text{cons-trail } (\text{Propagated } L (D + \{\#L\# \}))$ 
         $(\text{reduce-trail-to } M1$ 
           $(\text{add-learned-cls } (D + \{\#L\# \})$ 
             $(\text{update-backtrack-lvl } i$ 
               $(\text{update-conflicting } \text{None } S))))$ 
       $\implies \text{cdcl}_W\text{-M-level-inv } S$ 
       $\implies P S T$ 
  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 *cdcl_W-o-induct-lev2* = *cdcl_W-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-M-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-M-level-inv S
shows cdcl_W S' T'
using assms **by** (meson assms backtrack-state-eq-compatible bj cdcl_W.simps cdcl_W-bj.simps
 cdcl_W-o-rule-cases cdcl_W-rf.cases cdcl_W-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)

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-bj S' T'
using assms
by induction (auto
 intro: skip-state-eq-compatible backtrack-state-eq-compatible resolve-state-eq-compatible)

lemma tranclp-cdcl_W-bj-state-eq-compatible:

assumes
 cdcl_W-bj⁺⁺ S T **and** inv: cdcl_W-M-level-inv S **and**
 $S \sim S'$ **and**
 $T \sim T'$
shows cdcl_W-bj⁺⁺ S' T'

```

using assms
proof (induction arbitrary: S' T')
  case base
  then show ?case
    using cdclW-bj-state-eq-compatible by blast
next
  case (step T U) note IH = this(3)[OF this(4-5)]
  have cdclW++ S T
    using tranclp-mono[of cdclW-bj cdclW] other step.hyps(1) by blast
  then have cdclW-M-level-inv T
    using inv tranclp-cdclW-consistent-inv by blast
  then have cdclW-bj++ T T'
    using  $\langle U \sim T' \rangle$  cdclW-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

```

17.4.4 Conservation of some Properties

lemma *level-of-marked-ge-1*:

```

assumes
  cdclW S S' and
  inv: cdclW-M-level-inv S and
   $\forall L\ l. \text{Marked } L\ l \in \text{set } (\text{trail } S) \longrightarrow l > 0$ 
shows  $\forall L\ l. \text{Marked } L\ l \in \text{set } (\text{trail } S') \longrightarrow l > 0$ 
using assms apply (induct rule: cdclW-all-induct-lev2)
by (auto dest: union-in-get-all-marked-decomposition-is-subset simp: cdclW-M-level-inv-decomp)

```

lemma *cdcl_W-o-no-more-init-clss*:

```

assumes
  cdclW-o S S' and
  inv: cdclW-M-level-inv S
shows init-clss S = init-clss S'
using assms by (induct rule: cdclW-o-induct-lev2) (auto simp: cdclW-M-level-inv-decomp)

```

lemma *tranclp-cdcl_W-o-no-more-init-clss*:

```

assumes
  cdclW-o++ S S' and
  inv: cdclW-M-level-inv S
shows init-clss S = init-clss S'
using assms apply (induct rule: tranclp.induct)
by (auto dest: cdclW-o-no-more-init-clss
  dest!: tranclp-cdclW-consistent-inv dest: tranclp-mono-explicit[of cdclW-o - - cdclW]
  simp: other)

```

lemma *rtranclp-cdcl_W-o-no-more-init-clss*:

```

assumes
  cdclW-o** S S' and
  inv: cdclW-M-level-inv S
shows init-clss S = init-clss S'
using assms unfolding rtranclp-unfold by (auto intro: tranclp-cdclW-o-no-more-init-clss)

```

lemma *cdcl_W-init-clss*:

```

cdclW S T  $\implies$  cdclW-M-level-inv S  $\implies$  init-clss S = init-clss T
by (induct rule: cdclW-all-induct-lev2) (auto simp: cdclW-M-level-inv-def)

```

lemma *rtrancpl-cdcl_W-init-clss*:

*cdcl_W** S T \implies cdcl_W-M-level-inv S \implies init-clss S = init-clss T*

by (induct rule: *rtrancpl-induct*) (auto dest: *cdcl_W-init-clss rtrancpl-cdcl_W-consistent-inv*)

lemma *trancpl-cdcl_W-init-clss*:

*cdcl_W** S T \implies cdcl_W-M-level-inv S \implies init-clss S = init-clss T*

using *rtrancpl-cdcl_W-init-clss*[of S T] **unfolding** *rtrancpl-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*

$\wedge (\forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{init-clss } S \models_{pm} T)$

$\wedge \text{set } (\text{get-all-mark-of-propagated } (\text{trail } S)) \subseteq \text{set-mset } (\text{clauses } S))$

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: cdclW-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 rtrancpl-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: rtrancpl-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* $S' \longleftrightarrow$ (
 $(\forall T. \text{conflicting } S' = \text{Some } T \longrightarrow \text{atms-of } T \subseteq \text{atms-of-msu } (\text{init-clss } S'))$
 $\wedge (\forall L \text{ mark. Propagated } L \text{ mark} \in \text{set } (\text{trail } S') \longrightarrow \text{atms-of } (\text{mark}) \subseteq \text{atms-of-msu } (\text{init-clss } S'))$
 $\wedge \text{atms-of-msu } (\text{learned-clss } S') \subseteq \text{atms-of-msu } (\text{init-clss } S')$
 $\wedge \text{atm-of } ' (\text{lits-of } (\text{trail } S')) \subseteq \text{atms-of-msu } (\text{init-clss } S'))$)

lemma *no-strange-atm-decomp*:
 assumes *no-strange-atm* S
 shows *conflicting* S = *Some* 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
 $lev: cdcl_W\text{-}M\text{-level-inv} \ S$ and
 $conf: \forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{atms-of } T \subseteq \text{atms-of-msu } (\text{init-clss } S)$ and
 $marked: \forall L \text{ mark. } \text{Propagated } L \text{ mark} \in \text{set } (\text{trail } S)$
 $\longrightarrow \text{atms-of mark} \subseteq \text{atms-of-msu } (\text{init-clss } S)$ and
 $learned: \text{atms-of-msu } (\text{learned-clss } S) \subseteq \text{atms-of-msu } (\text{init-clss } S)$ and
 $trail: \text{atm-of } ' (\text{lits-of } (\text{trail } S)) \subseteq \text{atms-of-msu } (\text{init-clss } S)$
shows $(\forall T. \text{conflicting } S' = \text{Some } T \longrightarrow \text{atms-of } T \subseteq \text{atms-of-msu } (\text{init-clss } S')) \wedge$
 $(\forall L \text{ mark. } \text{Propagated } L \text{ mark} \in \text{set } (\text{trail } S')) \wedge$
 $\longrightarrow \text{atms-of } (\text{mark}) \subseteq \text{atms-of-msu } (\text{init-clss } S') \wedge$
 $\text{atms-of-msu } (\text{learned-clss } S') \subseteq \text{atms-of-msu } (\text{init-clss } S') \wedge$
 $\text{atm-of } ' (\text{lits-of } (\text{trail } S')) \subseteq \text{atms-of-msu } (\text{init-clss } S') \text{ (is } ?C \ S' \wedge ?M \ S' \wedge ?U \ S' \wedge ?V \ S')$
using $assms(1,2)$
proof (*induct rule: $cdcl_W\text{-all-induct-lev2}$*)
case (*propagate $C \ L \ T$*) **note** $C\text{-}L = \text{this}(1)$ **and** $undef = \text{this}(3)$ **and** $confl = \text{this}(4)$ **and** $T = \text{this}(5)$
have $?C \ (\text{cons-trail } (\text{Propagated } L \ (C + \{\#L\# \})) \ S)$ **using** $confl \ undef$ **by** *auto*
moreover
have $\text{atms-of } (C + \{\#L\# \}) \subseteq \text{atms-of-msu } (\text{init-clss } S)$
by (*metis (no-types) atms-of-atms-of-ms-mono atms-of-ms-union clauses-def mem-set-mset-iff*
 $C\text{-}L \text{ learned set-mset-union sup.orderE}$)
then have $?M \ (\text{cons-trail } (\text{Propagated } L \ (C + \{\#L\# \})) \ S)$ **using** $undef$
by (*simp add: marked*)
moreover have $?U \ (\text{cons-trail } (\text{Propagated } L \ (C + \{\#L\# \})) \ S)$
using $learned \ undef$ **by** *auto*
moreover have $?V \ (\text{cons-trail } (\text{Propagated } L \ (C + \{\#L\# \})) \ S)$
using $C\text{-}L \text{ learned trail undef unfolding clauses-def}$
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** $clauses\text{-}def$ **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** $T = \text{this}(4)$
have $D: \text{atm-of } ' \text{ set-mset } D \subseteq \bigcup (\text{atms-of } ' (\text{set-mset } (\text{clauses } S)))$
using $\langle D \in \# \text{ clauses } S \rangle$ **by** (*auto simp add: atms-of-def atms-of-ms-def*)
moreover {
fix $xa :: 'v \text{ literal}$
assume $a1: \text{atm-of } ' \text{ set-mset } D \subseteq (\bigcup x \in \text{set-mset } (\text{init-clss } S). \text{atms-of } x)$
 $\cup (\bigcup x \in \text{set-mset } (\text{learned-clss } S). \text{atms-of } x)$
assume $a2: (\bigcup x \in \text{set-mset } (\text{learned-clss } S). \text{atms-of } x) \subseteq (\bigcup x \in \text{set-mset } (\text{init-clss } S). \text{atms-of } x)$
assume $xa \in \# \ D$
then have $\text{atm-of } xa \in \text{UNION } (\text{set-mset } (\text{init-clss } S)) \text{ atms-of}$
using $a2 \ a1$ **by** (*metis (no-types) Un-iff atm-of-lit-in-atms-of atms-of-def subset-Un-eq*)
then have $\exists m \in \text{set-mset } (\text{init-clss } S). \text{atm-of } xa \in \text{atms-of } m$
by *blast*
} **note** $H = \text{this}$
ultimately show $?case$ **using** $\text{conflict.premis } T \text{ learned marked confl trail}$
unfolding $\text{atms-of-def atms-of-ms-def clauses-def}$
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:  $\bigwedge L$  mark. Propagated L 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  $\subseteq$  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 (Some (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 cdclW-no-strange-atm-inv:
  assumes cdclW S S' and no-strange-atm S and cdclW-M-level-inv S
  shows no-strange-atm S'
  using cdclW-no-strange-atm-explicit[OF assms(1)] assms(2,3) unfolding no-strange-atm-def by fast

lemma rtranclp-cdclW-no-strange-atm-inv:
  assumes cdclW** S S' and no-strange-atm S and cdclW-M-level-inv S
  shows no-strange-atm S'
  using assms by induction (auto intro: cdclW-no-strange-atm-inv rtranclp-cdclW-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* ($S::st$)
 $\longleftrightarrow ((\forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{distinct-mset } T)$
 $\wedge \text{distinct-mset-mset } (\text{learned-clss } S)$
 $\wedge \text{distinct-mset-mset } (\text{init-clss } S)$
 $\wedge (\forall L \text{ mark. } (\text{Propagated } L \text{ mark} \in \text{set } (\text{trail } S) \longrightarrow \text{distinct-mset } (\text{mark}))))$

lemma *distinct-cdcl_W-state-decomp*:
assumes *distinct-cdcl_W-state* ($S::st$)
shows $\forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{distinct-mset } T$
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 $\text{conflicting } S = \text{Some } T \implies \text{distinct-mset } T$
using *assms* **unfolding** *distinct-cdcl_W-state-def* **by** *auto*

lemma *distinct-cdcl_W-state-S0-cdcl_W[simp]*:
 $\text{distinct-mset-mset } N \implies \text{distinct-cdcl}_W\text{-state } (\text{init-state } N)$
unfolding *distinct-cdcl_W-state-def* **by** *auto*

lemma *distinct-cdcl_W-state-inv*:
assumes
 $\text{cdcl}_W \text{ } S \text{ } S'$ **and**
 $\text{cdcl}_W\text{-M-level-inv } S$ **and**
 $\text{distinct-cdcl}_W\text{-state } S$
shows $\text{distinct-cdcl}_W\text{-state } S'$
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*
 $\text{distinct-mset-single-add}$
 $\text{intro!}: \text{distinct-mset-union-mset}$)
qed (*auto simp add: distinct-cdcl_W-state-def distinct-mset-set-def clauses-def*)

lemma *rtanclp-distinct-cdcl_W-state-inv*:
assumes
 $\text{cdcl}_W^{**} \text{ } S \text{ } S'$ **and**
 $\text{cdcl}_W\text{-M-level-inv } S$ **and**

distinct-cdcl_W-state S
shows *distinct-cdcl_W-state S'*
using *assms apply (induct rule: rtrancpl-induct)*
using *distinct-cdcl_W-state-inv rtrancpl-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
 $\forall L \text{ mark } a \ b. \ a \ @ \ \text{Propagated } L \text{ mark } \# \ b = (\text{trail } S)$
 $\longrightarrow (b \models_{as} \text{CNot } (\text{mark} - \{\#L\}) \wedge L \in \# \text{ mark})$

definition *cdcl_W-conflicting S \equiv*
 $(\forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{trail } S \models_{as} \text{CNot } T)$
 $\wedge \text{every-mark-is-a-conflict } S$

lemma *backtrack-atms-of-D-in-M1:*

fixes *M1 :: ('v, nat, 'v clause) marked-lits*

assumes

inv: cdcl_W-M-level-inv S **and**

undef: undefined-lit M1 L **and**

i: get-maximum-level (trail S) D = i **and**

decomp: (Marked K (Suc i) # M1, M2)

$\in \text{set } (\text{get-all-marked-decomposition } (\text{trail } S))$ **and**

S-lvl: backtrack-lvl S = get-maximum-level (trail S) (D + {\#L\#}) **and**

S-conf: conflicting S = Some (D + {\#L\#}) **and**

undef: undefined-lit M1 L **and**

T: T \sim (cons-trail (Propagated L (D + {\#L\#}))

(reduce-trail-to M1

(add-learned-cls (D + {\#L\#})

(update-backtrack-lvl i

(update-conflicting None S)))) **and**

conf: $\forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{trail } S \models_{as} \text{CNot } T$

shows *atms-of D \subseteq atm-of ' lits-of (tl (trail T))*

proof (rule ccontr)

let *?k = get-maximum-level (trail S) (D + {\#L\#})*

have *trail S \models_{as} CNot D* **using** *conf S-conf* **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)

obtain *M0* **where** *M: trail S = M0 @ M2 @ Marked K (Suc i) # M1*

using *decomp* **by** *auto*

have *max: get-maximum-level (trail S) (D + {\#L\#})*

$= \text{length } (\text{get-all-levels-of-marked } (M0 @ M2 @ \text{Marked } K (Suc i) \# M1))$

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 atms-of D **and**

L'-notin-M1: L' \notin atm-of ' lits-of M1

using *T undef decomp inv* **by** (auto simp: *cdcl_W-M-level-inv-decomp*)

then have *L'-in: L' \in atm-of ' lits-of (M0 @ M2 @ 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 $L' L'$ -notin- $M1$ unfolding atms-of-def by auto
have $\text{lev-}L''$:
 $\text{get-level } (\text{trail } S) L'' = \text{get-rev-level } (\text{Marked } K (Suc\ i) \# \text{rev } M2 @ \text{rev } M0) (Suc\ i) L''$
using L' -notin- $M1$ $L'' M$ by $(\text{auto simp del: get-rev-level.simps})$
have $\text{get-all-levels-of-marked } (\text{trail } S) = \text{rev } [1..<1+?k]$
using $\text{inv } S\text{-lvl}$ unfolding $\text{cdcl}_W\text{-}M\text{-level-inv-def}$ by auto
then have $\text{get-all-levels-of-marked } (M0 @ M2)$
 $= \text{rev } [Suc\ (Suc\ i)..<Suc\ (\text{get-maximum-level } (\text{trail } S) (D + \{\#L\#}))]$
unfolding M by $(\text{auto simp: rev-swap[symmetric] dest!: append-cons-eq-upt-length-i-end})$

then have M : $\text{get-all-levels-of-marked } M0 @ \text{get-all-levels-of-marked } M2$
 $= \text{rev } [Suc\ (Suc\ i)..<Suc\ (\text{length } (\text{get-all-levels-of-marked } (M0 @ M2 @ \text{Marked } K (Suc\ i) \# M1)))]$
unfolding max unfolding M by simp

have $\text{get-rev-level } (\text{Marked } K (Suc\ i) \# \text{rev } (M0 @ M2)) (Suc\ i) L''$
 $\geq \text{Min } (\text{set } ((Suc\ i) \# \text{get-all-levels-of-marked } (\text{Marked } K (Suc\ i) \# \text{rev } (M0 @ M2))))$
using $\text{get-rev-level-ge-min-get-all-levels-of-marked}[of\ L'']$
 $\text{rev } (M0 @ M2 @ [\text{Marked } K (Suc\ i)])\ Suc\ i\ L'\text{-in}$
unfolding L'' by $(\text{fastforce simp add: lits-of-def})$
also have $\text{Min } (\text{set } ((Suc\ i) \# \text{get-all-levels-of-marked } (\text{Marked } K (Suc\ i) \# \text{rev } (M0 @ M2))))$
 $= \text{Min } (\text{set } ((Suc\ i) \# \text{get-all-levels-of-marked } (\text{rev } (M0 @ M2))))$ **by auto**
also have $\dots = \text{Min } (\text{set } ((Suc\ i) \# \text{get-all-levels-of-marked } M0 @ \text{get-all-levels-of-marked } M2))$
by $(\text{simp add: Un-commute})$
also have $\dots = \text{Min } (\text{set } ((Suc\ i) \# [Suc\ (Suc\ i)..<2 + \text{length } (\text{get-all-levels-of-marked } M0)$
 $+ (\text{length } (\text{get-all-levels-of-marked } M2) + \text{length } (\text{get-all-levels-of-marked } M1)))]))$
unfolding M by $(\text{auto simp add: Un-commute})$
also have $\dots = Suc\ i$ by $(\text{auto intro: Min-eqI})$
finally have $\text{get-rev-level } (\text{Marked } K (Suc\ i) \# \text{rev } (M0 @ M2)) (Suc\ i) L'' \geq Suc\ i$.
then have $\text{get-level } (\text{trail } S) L'' \geq i + 1$
using $\text{lev-}L''$ by simp
then have $\text{get-maximum-level } (\text{trail } S) D \geq i + 1$
using $\text{get-maximum-level-ge-get-level}[OF\ \langle L'' \in \# D \rangle, \text{ of trail } S]$ by auto
then show False using i by auto
qed

lemma $\text{distinct-atms-of-incl-not-in-other}$:

assumes
 $a1: \text{no-dup } (M @ M')$ **and $a2$:**
 $\text{atms-of } D \subseteq \text{atm-of } ' \text{ lits-of } M'$
shows $\forall x \in \text{atms-of } D. x \notin \text{atm-of } ' \text{ lits-of } M$
proof –
{ fix $aa :: 'a$
have $\text{ff1}: \bigwedge l\ ms. \text{undefined-lit } ms\ l \vee \text{atm-of } l$
 $\in \text{set } (\text{map } (\lambda m. \text{atm-of } (\text{lit-of } (m::('a, 'b, 'c) \text{ marked-lit})))\ ms)$
by $(\text{simp add: defined-lit-map})$
have $\text{ff2}: \bigwedge a. a \notin \text{atms-of } D \vee a \in \text{atm-of } ' \text{ lits-of } M'$
using $a2$ by (meson subsetCE)
have $\text{ff3}: \bigwedge a. a \notin \text{set } (\text{map } (\lambda m. \text{atm-of } (\text{lit-of } m))\ M')$
 $\vee a \notin \text{set } (\text{map } (\lambda m. \text{atm-of } (\text{lit-of } m))\ M)$
using $a1$ by $(\text{metis } (\text{lifting})\ \text{IntI}\ \text{distinct-append empty-iff map-append})$
have $\forall L\ a\ f. \exists l. ((a::'a) \notin f\ ' L \vee (l::'a\ \text{literal}) \in L) \wedge (a \notin f\ ' L \vee f\ l = a)$
by blast

```

    then have aa  $\notin$  atms-of  $D \vee$  aa  $\notin$  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:  $\forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{trail } S \models_{as} CNot\ T$  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  $tr = \text{this}(1)$  and  $T = \text{this}(4)$ 
  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  $tr = \text{this}(1)$  and  $T = \text{this}(5)$ 
  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  $S = \text{this}(1)$  and undef = this(2) and  $T = \text{this}(4)$ 
  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  $T = \text{this}(5)$ 
  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 unmark  $a \cup$  set-mset (init-clss  $S$ )  $\models_{ps}$  unmark  $y$ 

```

```

using decomp ay unfolding all-decomposition-implies-def
by (cases get-all-marked-decomposition (trail S)) fastforce+
then have a-Un-N-M: unmark a ∪ set-mset (init-clss S)
   $\models_{ps}$  unmark (trail S)
unfolding M by (auto simp add: all-in-true-clss-clss image-Un)

have unmark a ∪ set-mset (init-clss S)  $\models_p$  {#L#} (is ?I  $\models_p$  -)
proof (rule true-clss-clss-plus-CNot)
  show ?I  $\models_p C + \{#L#\}$ 
    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 ( $\lambda m. \{ \#lit\text{-}of\ m \# \}$ ) ‘set (trail S)  $\models_{ps}$  CNot C’
    using (trail S  $\models_{as}$  CNot C) true-annots-true-clss-clss by blast
  then show ?I  $\models_{ps}$  CNot C
    using a-Un-N-M true-clss-clss-left-right true-clss-clss-union-l-r by blast
qed
moreover have  $\bigwedge aa\ b.$ 
   $\forall (Ls, seen) \in set\ (get\text{-}all\text{-}marked\text{-}decomposition\ (y\ @\ a)).$ 
  unmark Ls ∪ set-mset (init-clss S)  $\models_{ps}$  unmark seen
 $\implies (aa, b) \in set\ (tl\ (get\text{-}all\text{-}marked\text{-}decomposition\ (y\ @\ a)))$ 
 $\implies unmark\ aa\ \cup\ set\text{-}mset\ (init\text{-}clss\ S)\ \models_{ps}\ unmark\ b$ 
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 (unmark a ∪ set-mset (init-clss S)  $\models_{ps}$  unmark 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  $\forall l \in set\ M2. \neg is\text{-}marked\ l$ 
  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 (cases ?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)  $\Rightarrow$  unmark Ls
  }

```

```

     $\cup$  set-mset (init-clss (T))
     $\models_{ps}$  unmark 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: unmark  $M1' \cup set-mset (init-clss S)$ 
     $\models_{ps}$  unmark  $M1''$ 
    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:
       $\forall x \in atms-of D. x \notin atm-of ' lits-of (M0 @ M2 @ Marked K (i + 1) \# [])$ 
      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]  $\langle trail S \models_{as} CNot D \rangle$  unfolding M lits-of-def by simp
    have  $M1 = M1'' @ M1'$  by (simp add: M1 get-all-marked-decomposition-decomp)
    have TT: unmark  $M1' \cup set-mset (init-clss S) \models_{ps}$  CNot D
      using true-annots-true-clss-cls[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': unmark  $M1' \cup set-mset (init-clss S) \models_p$  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 unmark  $M1' \cup set-mset (init-clss S) \models_p$   $\{\#L\}$ 
      using true-clss-cls-plus-CNot[OF T' TT] by auto
  ultimately
    have case x of (Ls, seen)  $\Rightarrow$  unmark Ls
       $\cup set-mset (init-clss T)$ 
       $\models_{ps}$  unmark seen using T' T decomp' undef inv unfolding x'
      by (simp add: cdclW-M-level-inv-decomp)
}
ultimately show case x of (Ls, seen)  $\Rightarrow$  unmark Ls  $\cup set-mset (init-clss T)$ 
 $\models_{ps}$  unmark 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-cls S) (get-all-marked-decomposition (trail S)) and

confl: $\forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{trail } S \models_{\text{as}} \text{CNot } T$ 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 *(trail S \models_{as} CNot C) 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 *$\bigwedge a \text{ La mark b. } a @ \text{Propagated La mark \# b} = \text{Marked L (backtrack-lvl S+1) \# trail S}$*

\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 *$\forall \text{La mark a b. } a @ \text{Propagated La mark \# b} = \text{Propagated L C' \# M}$*

\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' mark # b
  using T tr-S by auto
  then show b  $\models_{as}$  CNot ( mark - {#L'#})  $\wedge$  L'  $\in$  # 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: trail S = M0 @ M2 @ Marked K (i + 1) # M1
  using backtrack.hyps(1) by auto
have [simp]: trail (reduce-trail-to M1 (add-learned-cls (D + {#L#})
  (update-backtrack-lvl i (update-conflicting None S)))) = M1
  using decomp lev by (auto simp: cdclW-M-level-inv-decomp)
show ?case
proof (intro allI impI)
  fix La mark a b
  assume a @ Propagated La mark # b = trail T
  then have (a = []  $\wedge$  Propagated La mark = Propagated L (D + {#L#})  $\wedge$  b = M1)
     $\vee$  tl a @ Propagated La mark # b = M1
  using M T decomp undef by (cases a) (auto)
moreover {
  assume A: a = [] and
    P: Propagated La mark = Propagated L ( (D + {#L#})) and
    b: b = M1
  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] T backtrack lev confl by auto
  have no-dup (trail S) using lev by (auto simp: cdclW-M-level-inv-decomp)
  then have vars-in-M1:  $\forall x \in \text{atms-of } D. x \notin$ 
    atm-of ' lits-of (M0 @ M2 @ 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 ( mark - {#La#})  $\wedge$  La  $\in$  # mark

```

```

    using  $P\ b$  by auto
  }
  moreover {
    assume  $tl\ a\ @\ Propagated\ La\ mark\ \# \ b = M1$ 
    then obtain  $c'$  where  $c' @ Propagated\ La\ mark\ \# \ b = trail\ S$  unfolding  $M$  by auto
    then have  $b \models_{as} CNot\ (mark - \{\#La\}) \wedge La \in \# \ mark$ 
    using  $mark\text{-}confl$  by blast
  }
  ultimately show  $b \models_{as} CNot\ (mark - \{\#La\}) \wedge La \in \# \ mark$  by fast
qed
qed

```

lemma $cdcl_W\text{-}conflicting\text{-}is\text{-}false$:

```

assumes
   $cdcl_W\ S\ S'$  and
   $M\text{-}lev: cdcl_W\text{-}M\text{-}level\text{-}inv\ S$  and
   $confl\text{-}inv: \forall T. conflicting\ S = Some\ T \longrightarrow trail\ S \models_{as} CNot\ T$  and
   $marked\text{-}confl: \forall L\ mark\ a\ b. a @ Propagated\ L\ mark\ \# \ b = (trail\ S)$ 
     $\longrightarrow (b \models_{as} CNot\ (mark - \{\#L\}) \wedge L \in \# \ mark)$  and
   $dist: distinct\text{-}cdcl_W\text{-}state\ S$ 
shows  $\forall T. conflicting\ S' = Some\ T \longrightarrow trail\ S' \models_{as} CNot\ T$ 
using  $assms(1,2)$ 
proof (induct rule:  $cdcl_W\text{-}all\text{-}induct\text{-}lev2$ )
case ( $skip\ L\ C'\ M\ D$ ) note  $tr\text{-}S = this(1)$  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  $-L \in lits\text{-}of\ M$ 
    using  $in\text{-}CNot\text{-}implies\text{-}uminus(2)[of\ D\ L\ Propagated\ L\ C' \# M]$ 
     $\langle Propagated\ L\ C' \# M \models_{as} CNot\ D \rangle$  by  $simp$ 
    then show  $False$ 
    by ( $metis\ M\text{-}lev\ cdcl_W\text{-}M\text{-}level\text{-}inv\ decomp(1)\ consistent\text{-}interp\text{-}def\ insert\text{-}iff$ 
       $lits\text{-}of\text{-}cons\ marked\text{-}lit.sel(2)\ skip.hyps(1))$ 
  qed
ultimately show  $?case$ 
using  $skip.hyps(1-3)\ true\text{-}annots\text{-}CNot\text{-}lit\text{-}of\text{-}notin\text{-}skip\ T$  unfolding  $cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}def$ 
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  $tl\ (trail\ S) \models_{as} CNot\ C$  using  $tr\ assms(4)$  by  $fastforce$ 
moreover
  have  $distinct\text{-}mset\ (D + \{\#-L\})$  using  $confl\ dist$ 
  unfolding  $distinct\text{-}cdcl_W\text{-}state\text{-}def$  by auto
  then have  $-L \notin \# \ D$  unfolding  $distinct\text{-}mset\text{-}def$  by auto
  have  $M \models_{as} CNot\ D$ 
  proof -
    have  $Propagated\ L\ ((C + \{\#L\})) \# M \models_{as} CNot\ D \cup CNot\ \{\#-L\}$ 
    using  $confl\ tr\ confl\text{-}inv$  by  $force$ 
    then show  $?thesis$ 
    using  $M\text{-}lev\ \langle -L \notin \# \ D \rangle\ tr\ true\text{-}annots\text{-}lit\text{-}of\text{-}notin\text{-}skip$ 

```


unfolding *cdcl_W-M-level-inv-def* **by** *force*
qed
moreover assume *conflicting T = Some T'*
ultimately
show *trail T ⊨_{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 $\forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{trail } S \models_{as} \text{CNot } T$
and $\forall L \text{ mark } a \ b. a \ @ \ \text{Propagated } L \text{ mark } \# \ b = (\text{trail } S)$
 $\longrightarrow (b \models_{as} \text{CNot } (\text{mark} - \{\#L\# \}) \wedge L \in \# \text{ mark})$
using *assms unfolding cdcl_W-conflicting-def* **by** *blast+*

lemma *cdcl_W-conflicting-decomp2*:
assumes *cdcl_W-conflicting S* **and** *conflicting S = Some T*
shows *trail S ⊨_{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 = Some D
shows *trail S ⊨_{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 $rtranclp$ - $cdcl_W$ -all-inv:

assumes

$cdcl_W$: $rtranclp\ cdcl_W\ S\ S'$ **and**

1: all-decomposition-implies-m ($init_class\ S$) ($get_all_marked_decomposition\ (trail\ S)$) **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 ($init_class\ S'$) ($get_all_marked_decomposition\ (trail\ S')$) **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 ($induct\ rule$: $rtranclp$ -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 ($init_class\ (init_state\ N)$)

($get_all_marked_decomposition\ (trail\ (init_state\ N))$)

and $cdcl_W$ -learned-clause ($init_state\ N$)

and $\forall T.$ conflicting ($init_state\ N$) = Some $T \longrightarrow (trail\ (init_state\ N)) \models_{as} CNot\ T$

and no-strange-atm ($init_state\ N$)

and consistent-interp ($lits_of\ (trail\ (init_state\ N))$)

and $\forall L \text{ mark } a \ b. \ a \ @ \text{ Propagated } L \text{ mark } \# \ b = \text{ trail } (\text{init-state } N) \longrightarrow$
 $(b \models_{as} CNot \ (\text{ mark } - \{ \#L\# \}) \wedge L \in \# \text{ mark})$
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 *atms-of-msu* *U* = *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 *unmark* *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 $(\lambda a. \{ \#lit\text{-of } a\# \})$ ' (*set* *M*))

using *tot* **unfolding** *total-over-m-def* **by** *auto*

then have $I \models_s (\lambda a. \{ \#lit\text{-of } a\# \})$ ' (*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*: $I \models_s \text{unmark } M$ **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-cl-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-cl-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*) $\implies ?N \cup \{ \{ \#lit\text{-of } L\# \} \mid L. \text{is-marked } L \wedge L \in \text{set } ?M \} \models_{ps} \text{unmark } ?M$, 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 $\text{set-mset } N \models_{ps} \text{unmark } M$

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* $S' = \text{Some } \{\#\}$ **and**

learned: *cdcl_W-learned-clause* S

shows *unsatisfiable* ($\text{set-mset } (\text{init-clss } S)$)

using *assms*

proof –

have *cdcl_W-learned-clause* S' **using** *cdcl_W-learned-clss* *cdcl_W* *learned* *lev* **by** *auto*

then have $\text{init-clss } S' \models_{pm} \{\#\}$ **using** *assms*(3) **unfolding** *cdcl_W-learned-clause-def* **by** *auto*

then have $\text{init-clss } S \models_{pm} \{\#\}$

using *cdcl_W-init-clss*[*OF assms*(1) *lev*] **by** *auto*

then show *?thesis* **unfolding** *satisfiable-def true-clss-cls-def* **by** *auto*

qed

lemma *conflict-with-false-implies-terminated*:

assumes *cdcl_W* S S'

and *conflicting* $S = \text{Some } \{\#\}$

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: cdclW-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* ($S :: 'st$)
 $\longleftrightarrow (trail\ S \models_{asm} init-clss\ S$
 $\vee ((\forall L \in set\ (trail\ S). \neg is-marked\ L) \wedge$
 $(\exists C \in \# init-clss\ S. trail\ S \models_{as} CNot\ C)))$

definition *termination-cdcl_W-state* ($S :: 'st$)
 $\longleftrightarrow (trail\ S \models_{asm} init-clss\ S$
 $\vee ((\forall L \in atms-of-msu\ (init-clss\ S). L \in atm-of\ ' lits-of\ (trail\ S))$
 $\wedge (\exists C \in \# init-clss\ S. trail\ S \models_{as} CNot\ C)))$

17.5 CDCL Strong Completeness

fun *mapi* :: ($'a \Rightarrow nat \Rightarrow 'b \Rightarrow nat \Rightarrow 'a\ list \Rightarrow 'b\ list$ **where**
mapi - - $\square = \square \mid$
mapi $f\ n\ (x \# xs) = f\ x\ n \# mapi\ f\ (n - 1)\ xs$

lemma *mark-not-in-set-mapi*[simp]: $L \notin set\ M \implies Marked\ L\ k \notin set\ (mapi\ Marked\ i\ M)$
by (induct M arbitrary: i) auto

lemma *propagated-not-in-set-mapi*[simp]: $L \notin set\ M \implies Propagated\ L\ k \notin set\ (mapi\ Marked\ i\ M)$
by (induct M arbitrary: i) auto

lemma *image-set-mapi*:
 $f\ ' set\ (mapi\ g\ i\ M) = set\ (mapi\ (\lambda x\ i. f\ (g\ x\ i))\ i\ M)$
by (induction M arbitrary: i) auto

lemma *mapi-map-convert*:
 $\forall x\ i\ j. f\ x\ i = f\ x\ j \implies mapi\ f\ i\ M = map\ (\lambda x. f\ x\ 0)\ M$
by (induction M arbitrary: i) auto

lemma *defined-lit-mapi*: *defined-lit* ($mapi\ Marked\ i\ M$) $L \longleftrightarrow atm-of\ L \in atm-of\ ' set\ M$
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**
 $atm-of\ ' (set\ M) \subseteq atms-of-msu\ N$
shows $\exists S. rtranc\ cdcl_W\ (init-state\ N)\ S$
 $\wedge state\ S = (mapi\ Marked\ (length\ M)\ M, N, \{\#\}, length\ M, None)$
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** $atm-of\ ' set\ M \subseteq atms-of-msu\ N$
using *Cons.premis(1-3)* **unfolding** *consistent-interp-def* **by** auto
then obtain S **where**

```

  st: cdclW** (init-state N) S and
  S: state S = (mapi Marked (length M) M, N, {#}, length M, None)
  using IH by auto
let ?S0 = 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, None) 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, None)
  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 option.simps(3)
    conflicting-update-conflicting state-eq-conflicting tranclp.intros(1))

```

qed

inductive $cdcl_W\text{-}cp :: 'st \Rightarrow 'st \Rightarrow bool$ **where**
conflict'[intro]: $conflict\ S\ S' \Longrightarrow cdcl_W\text{-}cp\ S\ S' \mid$
propagate': $propagate\ S\ S' \Longrightarrow cdcl_W\text{-}cp\ S\ S'$

lemma $rtrancp\text{-}cdcl_W\text{-}cp\text{-}rtrancp\text{-}cdcl_W$:
 $cdcl_W\text{-}cp^{**}\ S\ T \Longrightarrow cdcl_W^{**}\ S\ T$
by (*induction rule*: $rtrancp\text{-}induct$) (*auto simp*: $cdcl_W\text{-}cp.simps$ *dest*: $cdcl_W.intros$)

lemma $cdcl_W\text{-}cp\text{-}state\text{-}eq\text{-}compatible$:
assumes
 $cdcl_W\text{-}cp\ S\ T$ **and**
 $S \sim S'$ **and**
 $T \sim T'$
shows $cdcl_W\text{-}cp\ S'\ T'$
using *assms*
apply (*induction*)
using *conflict-state-eq-compatible* **apply** *auto*[1]
using *propagate'* *propagate-state-eq-compatible* **by** *auto*

lemma $trancp\text{-}cdcl_W\text{-}cp\text{-}state\text{-}eq\text{-}compatible$:
assumes
 $cdcl_W\text{-}cp^{++}\ S\ T$ **and**
 $S \sim S'$ **and**
 $T \sim T'$
shows $cdcl_W\text{-}cp^{++}\ S'\ T'$
using *assms*
proof *induction*
case *base*
then show ?*case*
using $cdcl_W\text{-}cp\text{-}state\text{-}eq\text{-}compatible$ **by** *blast*
next
case (*step* $U\ V$)
obtain $ss :: 'st$ **where**
 $cdcl_W\text{-}cp\ S\ ss \wedge cdcl_W\text{-}cp^{**}\ ss\ U$
by (*metis* (*no-types*) *step*(1) *trancpD*)
then show ?*case*
by (*meson* $cdcl_W\text{-}cp\text{-}state\text{-}eq\text{-}compatible\ rtrancp.rtrancp\text{-}into\text{-}rtrancp\ rtrancp\text{-}into\text{-}trancp2$
 $state\text{-}eq\text{-}ref\ step(2)\ step(4)\ step(5)$)
qed

lemma $option\text{-}full\text{-}cdcl_W\text{-}cp$:
 $conflicting\ S \neq None \Longrightarrow full\ cdcl_W\text{-}cp\ S\ S$
unfolding $full\text{-}def\ rtrancp\text{-}unfold\ trancp\text{-}unfold$ **by** (*auto simp add*: $cdcl_W\text{-}cp.simps$)

lemma $skip\text{-}unique$:
 $skip\ S\ T \Longrightarrow skip\ S\ T' \Longrightarrow T \sim T'$
by (*fastforce simp*: $state\text{-}eq\text{-}def\ simp\ del$: $state\text{-}simp$)

lemma $resolve\text{-}unique$:
 $resolve\ S\ T \Longrightarrow resolve\ S\ T' \Longrightarrow T \sim T'$
by (*fastforce simp*: $state\text{-}eq\text{-}def\ simp\ del$: $state\text{-}simp$)

lemma $cdcl_W\text{-}cp\text{-}no\text{-}more\text{-}clauses$:

```

assumes  $cdcl_W\text{-}cp\ S\ S'$ 
shows  $clauses\ S = clauses\ S'$ 
using assms by (induct rule:  $cdcl_W\text{-}cp.induct$ ) (auto elim!:  $conflictE\ propagateE$ )

lemma  $trancpl\text{-}cdcl_W\text{-}cp\text{-}no\text{-}more\text{-}clauses$ :
assumes  $cdcl_W\text{-}cp^{++}\ S\ S'$ 
shows  $clauses\ S = clauses\ S'$ 
using assms by (induct rule:  $trancpl.induct$ ) (auto dest:  $cdcl_W\text{-}cp\text{-}no\text{-}more\text{-}clauses$ )

lemma  $rtrancpl\text{-}cdcl_W\text{-}cp\text{-}no\text{-}more\text{-}clauses$ :
assumes  $cdcl_W\text{-}cp^{**}\ S\ S'$ 
shows  $clauses\ S = clauses\ S'$ 
using assms by (induct rule:  $rtrancpl.induct$ ) (fastforce dest:  $cdcl_W\text{-}cp\text{-}no\text{-}more\text{-}clauses$ )

lemma  $no\text{-}conflict\text{-}after\text{-}conflict$ :
 $conflict\ S\ T \implies \neg conflict\ T\ U$ 
by fastforce

lemma  $no\text{-}propagate\text{-}after\text{-}conflict$ :
 $conflict\ S\ T \implies \neg propagate\ T\ U$ 
by fastforce

lemma  $trancpl\text{-}cdcl_W\text{-}cp\text{-}propagate\text{-}with\text{-}conflict\text{-}or\text{-}not$ :
assumes  $cdcl_W\text{-}cp^{++}\ S\ U$ 
shows ( $propagate^{++}\ S\ U \wedge conflicting\ U = None$ )
 $\vee (\exists T\ D. propagate^{**}\ S\ T \wedge conflict\ T\ U \wedge conflicting\ U = Some\ D)$ 
proof –
have  $propagate^{++}\ S\ U \vee (\exists T. propagate^{**}\ S\ T \wedge conflict\ T\ U)$ 
using assms by induction
(force simp:  $cdcl_W\text{-}cp.simps\ trancpl\text{-}into\text{-}rtrancpl\ dest$ :  $no\text{-}conflict\text{-}after\text{-}conflict$ 
 $no\text{-}propagate\text{-}after\text{-}conflict$ )
moreover
have  $propagate^{++}\ S\ U \implies conflicting\ U = None$ 
unfolding  $trancpl\text{-}unfold\text{-}end$  by auto
moreover
have  $\bigwedge T. conflict\ T\ U \implies \exists D. conflicting\ U = Some\ D$ 
by auto
ultimately show ?thesis by meson
qed

lemma  $cdcl_W\text{-}cp\text{-}conflicting\text{-}not\text{-}empty[simp]$ :  $conflicting\ S = Some\ D \implies \neg cdcl_W\text{-}cp\ S\ S'$ 
proof
assume  $cdcl_W\text{-}cp\ S\ S'$  and  $conflicting\ S = Some\ D$ 
then show False by (induct rule:  $cdcl_W\text{-}cp.induct$ ) auto
qed

lemma  $no\text{-}step\text{-}cdcl_W\text{-}cp\text{-}no\text{-}conflict\text{-}no\text{-}propagate$ :
assumes  $no\text{-}step\ cdcl_W\text{-}cp\ S$ 
shows  $no\text{-}step\ conflict\ S$  and  $no\text{-}step\ propagate\ S$ 
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 $cdcl_W\text{-}o\ S\ S'$ and re-apply conflict and propagate *full* $cdcl_W\text{-}cp\ S'\ S''$

inductive $cdcl_W\text{-stgy} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **for** $S :: 'st$ **where**
conflict': $\text{full1 } cdcl_W\text{-cp } S \ S' \Longrightarrow cdcl_W\text{-stgy } S \ S' \mid$
other': $cdcl_W\text{-o } S \ S' \Longrightarrow \text{no-step } cdcl_W\text{-cp } S \Longrightarrow \text{full } cdcl_W\text{-cp } S' \ S'' \Longrightarrow cdcl_W\text{-stgy } S \ S''$

17.6.2 Invariants

These are the same invariants as before, but lifted

lemma $cdcl_W\text{-cp-learned-clause-inv}$:

assumes $cdcl_W\text{-cp } S \ S'$

shows $\text{learned-clss } S = \text{learned-clss } S'$

using *assms* **by** (*induct rule*: $cdcl_W\text{-cp.induct}$) *fastforce*+

lemma $rtrancpl\text{-}cdcl_W\text{-cp-learned-clause-inv}$:

assumes $cdcl_W\text{-cp}^{**} S \ S'$

shows $\text{learned-clss } S = \text{learned-clss } S'$

using *assms* **by** (*induct rule*: $rtrancpl\text{-induct}$) (*fastforce dest*: $cdcl_W\text{-cp-learned-clause-inv}$)+

lemma $trancpl\text{-}cdcl_W\text{-cp-learned-clause-inv}$:

assumes $cdcl_W\text{-cp}^{++} S \ S'$

shows $\text{learned-clss } S = \text{learned-clss } S'$

using *assms* **by** (*simp add*: $rtrancpl\text{-}cdcl_W\text{-cp-learned-clause-inv } \text{trancpl-into-rtrancpl}$)

lemma $cdcl_W\text{-cp-backtrack-lvl}$:

assumes $cdcl_W\text{-cp } S \ S'$

shows $\text{backtrack-lvl } S = \text{backtrack-lvl } S'$

using *assms* **by** (*induct rule*: $cdcl_W\text{-cp.induct}$) *fastforce*+

lemma $rtrancpl\text{-}cdcl_W\text{-cp-backtrack-lvl}$:

assumes $cdcl_W\text{-cp}^{**} S \ S'$

shows $\text{backtrack-lvl } S = \text{backtrack-lvl } S'$

using *assms* **by** (*induct rule*: $rtrancpl\text{-induct}$) (*fastforce dest*: $cdcl_W\text{-cp-backtrack-lvl}$)+

lemma $cdcl_W\text{-cp-consistent-inv}$:

assumes $cdcl_W\text{-cp } S \ S'$

and $cdcl_W\text{-M-level-inv } S$

shows $cdcl_W\text{-M-level-inv } S'$

using *assms*

proof (*induct rule*: $cdcl_W\text{-cp.induct}$)

case (*conflict'*)

then show ?*case* **using** $cdcl_W\text{-consistent-inv } cdcl_W.\text{conflict}$ **by** *blast*

next

case (*propagate'* $S \ S'$)

have $cdcl_W \ S \ S'$

using $\text{propagate'}.hyps(1)$ *propagate* **by** *blast*

then show $cdcl_W\text{-M-level-inv } S'$

using $\text{propagate'}.prems(1)$ $cdcl_W\text{-consistent-inv } \text{propagate}$ **by** *blast*

qed

lemma $\text{full1-}cdcl_W\text{-cp-consistent-inv}$:

assumes $\text{full1 } cdcl_W\text{-cp } S \ S'$

and $cdcl_W\text{-M-level-inv } S$

shows $cdcl_W\text{-M-level-inv } S'$

using *assms* **unfolding** full1-def

proof –

have $cdcl_W\text{-cp}^{++} S \ S'$ **and** $cdcl_W\text{-M-level-inv } S$ **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 *rtrancpl 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: *rtrancpl-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 *rtrancpl-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 *trancpl-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: *trancpl.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: *trancpl-cdcl_W-cp-no-more-init-clss trancpl-cdcl_W-o-no-more-init-clss*)
by (metis *cdcl_W-o-no-more-init-clss rtrancpl-unfold trancpl-cdcl_W-cp-no-more-init-clss*)

lemma *rtrancpl-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: *rtrancpl-induct, simp*)
using *cdcl_W-stgy-no-more-init-clss* **by** (simp add: *rtrancpl-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** $(\forall l \in \text{set } M. \neg \text{is-marked } l)$
using *assms by induction fastforce* +

lemma *rtrancp-cdcl_W-cp-dropWhile-trail'*:
assumes *cdcl_W-cp** S S'*
obtains *M :: ('v, nat, 'v clause) marked-lit list* **where**
trail S' = M @ trail S and $\forall l \in \text{set } M. \neg \text{is-marked } l$
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 $\text{length (trail } S) \leq \text{card (atms-of-msu (init-clss } S))$
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 $\text{length (trail } S) = \text{card (atm-of ' lits-of (trail } S))$
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 $(\lambda S. \text{card (atms-of-msu (init-clss } S)) - \text{length (trail } S))$
 $+ (\text{if conflicting } S = \text{None then } 1 \text{ else } 0)) S$
 $> (\lambda S. \text{card (atms-of-msu (init-clss } S)) - \text{length (trail } S))$
 $+ (\text{if conflicting } S = \text{None then } 1 \text{ else } 0)) T$
using *assms*
proof –
have $\text{length (trail } T) \leq \text{card (atms-of-msu (init-clss } T))$
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*: $\text{wf } \{(b, a). (\text{cdcl}_W\text{-M-level-inv } a \wedge \text{no-strange-atm } a) \wedge \text{cdcl}_W\text{-cp } a \text{ } b\}$

```

apply (rule wf-wf-if-measure'[of less-than - -
  ( $\lambda S. \text{card} (\text{atms-of-msu} (\text{init-clss } S)) - \text{length} (\text{trail } S)$ 
  + (if conflicting  $S = \text{None}$  then 1 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 ( $\lambda a b. (\text{cdcl}_W\text{-M-level-inv } a \wedge \text{no-strange-atm } a) \wedge \text{cdcl}_W\text{-cp } a b$ )**  $S T$ 
 $\longleftrightarrow$  cdclW-cp**  $S T$ 
(is ?I  $S T \longleftrightarrow ?C S T$ )
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 ( $\lambda a b. (\text{cdcl}_W\text{-M-level-inv } a \wedge \text{no-strange-atm } a)$ 
 $\wedge \text{cdcl}_W\text{-cp } a b$ )**  $T U$ 
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 =  $\lambda a. (\text{cdcl}_W\text{-M-level-inv } a \wedge \text{no-strange-atm } a)$ 
obtain  $T$  where  $T$ : full ( $\lambda a b. ?inv a \wedge \text{cdcl}_W\text{-cp } a b$ )  $S T$ 
using cdclW-cp-wf wf-exists-normal-form[of  $\lambda a b. ?inv a \wedge \text{cdcl}_W\text{-cp } a b$ ]
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 $cdcl_W^{**} S T$
using $rtrancpl-cdcl_W-cp-rtrancpl-cdcl_W$ **by** *blast*
then have
 $cdcl_W-M-level-inv T$ **and**
 $no-strange-atm T$
using $\langle cdcl_W^{**} S T \rangle$ **apply** (*simp add: assms(1) rtrancpl-cdcl_W-consistent-inv*)
using $\langle cdcl_W^{**} S T \rangle$ *assms(2) rtrancpl-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:*
 $C + \{\#L\# \} \in \# A \implies x \in atm\text{-of } C \implies x \in atm\text{-of-msu } A$
by (*metis add.commute atm-iff-pos-or-neg-lit atm\text{-of-atms-of-ms-mono contra-subsetD mem-set-mset-iff multi-member-skip*)

lemma *propagate-no-stange-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 $\exists S''. full\ cdcl_W-cp\ S\ S''$
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 $atm: atm\text{-of-msu } (init-clss S) = atm\text{-of } 'lits\text{-of } (trail S)$
unfolding *no-strange-atm-def* **by** *auto*
{ **assume** $a: \exists S'. conflict\ S\ S'$
then obtain S' **where** $S': conflict\ S\ S'$ **by** *metis*
then have $\forall S''. \neg cdcl_W-cp\ S'\ S''$ **by** *auto*
then have *?case* **using** $a\ S'\ cdcl_W-cp.conflict'$ **unfolding** *full-def* **by** *blast*
}
moreover {
assume $a: \exists S'. propagate\ S\ S'$
then obtain S' **where** $propagate\ S\ S'$ **by** *blast*
then obtain $M\ N\ U\ k\ C\ L$ **where** $S: state\ S = (M, N, U, k, None)$
and $S': state\ S' = (Propagated\ L\ (C + \{\#L\#\})) \# M, N, U, k, None)$
and $C + \{\#L\#\} \in \# clauses\ S$
and $M \models_{as} CNot\ C$
and $undefined-lit\ M\ L$
using *propagate* **by** *auto*
have $atms\text{-of-msu } U \subseteq atm\text{-of-msu } N$ **using** *alien S* **unfolding** *no-strange-atm-def* **by** *auto*
then have $atm\text{-of } L \in atm\text{-of-msu } (init-clss S)$
using $\langle C + \{\#L\#\} \in \# clauses\ S \rangle$ S **unfolding** *atms-of-ms-def clauses-def* **by** *force+*
then have *False* **using** $\langle undefined-lit\ M\ L \rangle S$ **unfolding** *atm* **unfolding** *lits-of-def*
by (*auto simp add: defined-lit-map*)
}
ultimately show *?case* **by** (*metis cdcl_W-cp.cases full-def rtrancpl.rtrancpl-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':  $\text{conflict } S S'$  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, None) and
    S': state S' = (Propagated L (C + {#L#})) # M, N, U, k, None) and
    C + {#L#}  $\in \#$  clauses S and
    M  $\models_{as}$  CNot C and
    undefined-lit M L
    by fastforce
  then have atm-of L  $\notin$  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 atm-of L  $\in$  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 Suc n - card {atm-of L} = n by simp
  moreover have card (atms-of-msu N - atm-of ' lits-of M) = Suc n
    using card S S' by simp
  ultimately
    have card (atms-of-msu N - atm-of ' insert L (lits-of M)) = n
      by (metis (no-types) Diff-insert card-Diff-subset finite.emptyI finite.insertI image-insert)
    then have n = card (atms-of-msu (init-clss S') - atm-of ' lits-of (trail S'))
      using card S S' by simp
  then have a1: Ex (full  $\text{cdcl}_W\text{-cp } S'$ ) using IH <no-strange-atm S'> by blast
  have ?case
    proof -
      obtain S'' :: 'st where
        ff1:  $\text{cdcl}_W\text{-cp}^{**} S' S'' \wedge \text{no-step } \text{cdcl}_W\text{-cp } S''$ 
        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 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 *local.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 *no-clause-is-false* :: 'st \Rightarrow bool **where**

no-clause-is-false \equiv

$\lambda S. (\text{conflicting } S = \text{None} \longrightarrow (\forall D \in \# \text{ clauses } S. \neg \text{trail } S \models_{as} \text{CNot } D))$

abbreviation *conflict-is-false-with-level* $:: 'st \Rightarrow \text{bool}$ **where**

conflict-is-false-with-level $S \equiv \forall D. \text{conflicting } S = \text{Some } D \longrightarrow D \neq \{\#\}$
 $\longrightarrow (\exists L \in \# D. \text{get-level } (\text{trail } S) L = \text{backtrack-lvl } S)$

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 *rtrancpl-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: *rtrancpl-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 *rtrancpl-cdcl_W-cp-propa-or-propa-confl*:

assumes *cdcl_W-cp*** $S U$

```

shows propagate** S U  $\vee$  ( $\exists T$ . propagate** S T  $\wedge$  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 = Some D and
    D: D  $\neq$  {#}
  consider (CT) conflicting S = None | (SD) D' where conflicting S = Some D'
  by (cases conflicting S) auto
  then show  $\exists L \in \#D$ . get-level (trail U) L = 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  $\bigwedge p$  pa.  $\neg$  propagate p pa  $\vee$  conflicting pa =
        (None::'v literal multiset option)
      by auto
      then show ?thesis
    end
  end
end

```



```

    using f5 that tranclp-cdclW-cp-propagate-with-conflict-or-not[OF ⟨cdclW-cp++ S U⟩]
    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 ⟨init-clss U = init-clss S⟩ ⟨learned-clss U = learned-clss S⟩ by auto
then have D ∈# clauses S
  using TU confl by (fastforce simp: clauses-def)
then have ¬ trail S ⊨as CNot D
  using cls-f CT by simp
moreover
  obtain M where tr-U: trail U = M @ trail S and nm: ∀ m ∈ set M. ¬ is-marked m
    by (metis (mono-tags, lifting) assms(1) full-def rtranclp-cdclW-cp-dropWhile-trail)
  have trail U ⊨as CNot D
    using TU confl by auto
ultimately obtain L where L ∈# D and ¬L ∈ lits-of M
  unfolding tr-U CNot-def true-annot-def Ball-def true-annot-def true-cl-def by auto

moreover have inv-U: cdclW-M-level-inv U
  by (metis cdclW-stgy.conflict' cdclW-stgy-consistent-inv full full-unfold lev)
moreover
  have backtrack-lvl U = backtrack-lvl S
    using full unfolding full-def by (auto dest: rtranclp-cdclW-cp-backtrack-lvl)

moreover
  have no-dup (trail U)
    using inv-U unfolding cdclW-M-level-inv-def by auto
  { fix x :: ('v, nat, 'v literal multiset) marked-lit and
    xb :: ('v, nat, 'v literal multiset) marked-lit
    assume a1: atm-of L = atm-of (lit-of xb)
    moreover assume a2: ¬ L = lit-of x
    moreover assume a3: (λl. atm-of (lit-of l)) ' set M
      ∩ (λl. atm-of (lit-of l)) ' set (trail S) = {}
    moreover assume a4: x ∈ set M
    moreover assume a5: xb ∈ set (trail S)
    moreover have atm-of (¬ L) = atm-of L
      by auto
    ultimately have False
      by auto
  }
then have LS: atm-of L ∉ atm-of ' lits-of (trail S)
  using ⟨¬L ∈ lits-of M⟩ ⟨no-dup (trail U)⟩ unfolding tr-U lits-of-def by auto
ultimately have get-level (trail U) L = backtrack-lvl U
proof (cases get-all-levels-of-marked (trail S) ≠ [], goal-cases)
  case 2 note LD = this(1) and LM = this(2) and inv-U = this(3) and US = this(4) and
    LS = this(5) and ne = this(6)
  have backtrack-lvl S = 0
    using lev ne unfolding cdclW-M-level-inv-def by auto
  moreover have get-rev-level (rev M) 0 L = 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 = this(1) and LM = this(2) and inv-U = this(3) and US = this(4) and
    LS = this(5) and ne = this(6)

```

```

have hd (get-all-levels-of-marked (trail S)) = backtrack-lvl S
  using ne lev unfolding cdclW-M-level-inv-def
  by (cases get-all-levels-of-marked (trail S)) auto
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 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 ∃ L ∈ #D. get-level (trail U) L = backtrack-lvl U
  using ⟨L ∈ # D⟩ by blast
qed
qed

```

17.6.4 Literal of highest level in marked literals

definition *mark-is-false-with-level* :: 'st ⇒ bool **where**
mark-is-false-with-level S' ≡
 ∀ D M1 M2 L. M1 @ Propagated L D # M2 = trail S' ⟶ D - {#L#} ≠ {#}
 ⟶ (∃ L. L ∈ # D ∧ get-level (trail S') L = get-maximum-possible-level M1)

definition *no-more-propagation-to-do*:: 'st ⇒ bool **where**
no-more-propagation-to-do S ≡
 ∀ D M M' L. D + {#L#} ∈ # clauses S ⟶ trail S = M' @ M ⟶ M ⊨_{as} CNot D
 ⟶ undefined-lit M L ⟶ get-maximum-possible-level M < backtrack-lvl S
 ⟶ (∃ L. L ∈ # D ∧ get-level (trail S) L = 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, None) **and**
 S': state S' = (Propagated L ((C + {#L#}))) # M, N, U, k, None) **and**
 C + {#L#} ∈ # clauses S **and**
 M ⊨_{as} CNot C **and**
 undefined-lit M L
using *propagate* **by** auto
let ?M' = 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'#} ∈ # clauses S'
and trail S' = M2 @ M1
and get-max: get-maximum-possible-level M1 < backtrack-lvl S'
and M1 ⊨_{as} CNot D
and undef: undefined-lit M1 L'
have tl M2 @ M1 = trail S ∨ (M2 = [] ∧ M1 = Propagated L ((C + {#L#}))) # M)
using (trail S' = M2 @ M1) S' S **by** (cases M2) auto

```

moreover {
  assume  $tl\ M2\ @\ M1 = trail\ S$ 
  moreover have  $D + \{\#L'\#\} \in \# \text{ clauses } S$  using  $D-L\ S\ S'$  unfolding  $clauses-def$  by  $auto$ 
  moreover have  $get-maximum-possible-level\ M1 < backtrack-lvl\ S$ 
    using  $get-max\ S\ S'$  by  $auto$ 
  ultimately obtain  $L'$  where  $L' \in \# D$  and
     $get-level\ (trail\ S)\ L' = get-maximum-possible-level\ M1$ 
    using  $H\ \langle M1 \models_{as} CNot\ D \rangle$  undef unfolding  $no-more-propagation-to-do-def$  by  $metis$ 
  moreover
    { have  $cdcl_W-M-level-inv\ S'$ 
      using  $cdcl_W-consistent-inv[OF - M]\ cdcl_W.propagate[OF\ propagate]$  by  $blast$ 
      then have  $no-dup\ ?M'$  using  $S'$  unfolding  $cdcl_W-M-level-inv-def$  by  $auto$ 
      moreover
        have  $atm-of\ L' \in atm-of\ ' (lits-of\ M1)$ 
          using  $\langle L' \in \# D \rangle\ \langle M1 \models_{as} CNot\ D \rangle$  by  $(metis\ atm-of-uminus\ image-eqI\ in-CNot-implies-uminus(2))$ 
          then have  $atm-of\ L' \in atm-of\ ' (lits-of\ M)$ 
            using  $\langle tl\ M2\ @\ M1 = trail\ S \rangle\ S$  by  $auto$ 
            ultimately have  $atm-of\ L \neq atm-of\ L'$  unfolding  $lits-of-def$  by  $auto$ 
        }
      ultimately have  $\exists L' \in \# D. get-level\ (trail\ S')\ L' = get-maximum-possible-level\ M1$ 
        using  $S\ S'$  by  $auto$ 
    }
  }
moreover {
  assume  $M2 = []$  and  $M1: M1 = Propagated\ L\ ( (C + \{\#L\#\}) \# M$ 
  have  $cdcl_W-M-level-inv\ S'$ 
    using  $cdcl_W-consistent-inv[OF - M]\ cdcl_W.propagate[OF\ propagate]$  by  $blast$ 
    then have  $get-all-levels-of-marked\ (trail\ S') = rev\ ([Suc\ 0..<(Suc\ 0+k)])$ 
      using  $S'$  unfolding  $cdcl_W-M-level-inv-def$  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  $\exists L. L \in \# D \wedge get-level\ (trail\ S')\ L = get-maximum-possible-level\ M1$  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  $M: cdcl_W-M-level-inv\ S$ 
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  $conflict: cdcl_W-cp\ S\ S'$ 
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  $(induct\ rule: cdcl_W-cp.induct)$ 
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: cdclW-o S S' and
  alien: no-strange-atm S and
  lev: cdclW-M-level-inv S
shows  $\exists S'. \text{cdcl}_W\text{-stgy } S S'$ 
proof -
obtain S'' where full cdclW-cp S' S''
  using always-exists-full-cdclW-cp-step alien cdclW-no-strange-atm-inv cdclW-o-no-more-init-clss
  o other lev by (meson cdclW-consistent-inv)
then show ?thesis
  using assms by (metis always-exists-full-cdclW-cp-step cdclW-stgy.conflict' full-unfold other')
qed

```

lemma *backtrack-no-decomp*:

```

assumes S: state S = (M, N, U, k, Some (D + {#L#}))
and L: get-level M L = k
and D: get-maximum-level M D < k
and M-L: cdclW-M-level-inv S
shows  $\exists S'. \text{cdcl}_W\text{-o } S S'$ 
proof -
have L-D: get-level M L = get-maximum-level M (D + {#L#})
  using L D by (simp add: get-maximum-level-plus)
let ?i = get-maximum-level M D
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 cdclW-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: cdclW-learned-clause S
and level-inv: cdclW-M-level-inv S
and alien: no-strange-atm S
and no-dup: distinct-cdclW-state S
and confl: cdclW-conflicting S
and confl-k: conflict-is-false-with-level S
shows (conflicting S = Some {#}  $\wedge$  unsatisfiable (set-mset (init-clss S)))
   $\vee$  (conflicting S = None  $\wedge$  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 = Some {#}
   $\vee$  conflicting S = None
   $\vee$  ( $\exists D L. \text{conflicting } S = \text{Some } (D + \{ \#L\# \})$ )
apply (cases conflicting S, auto)

```

```

by (rename-tac C, case-tac C, auto)
moreover {
  assume conflicting S = Some {#}
  then have unsatisfiable (set-mset (init-clss S))
    using assms(3) unfolding cdclW-learned-clause-def true-clss-cls-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 = None
  { assume ¬?M ⊨asm ?N
    have atm-of ' (lits-of ?M) = atms-of-msu ?N (is ?A = ?B)
    proof
      show ?A ⊆ ?B using alien unfolding no-strange-atm-def by auto
      show ?B ⊆ ?A
        proof (rule ccontr)
          assume ¬?B ⊆ ?A
          then obtain l where l ∈ ?B and l ∉ ?A by auto
          then have undefined-lit ?M (Pos l)
            using ⟨l ∉ ?A⟩ unfolding lits-of-def by (auto simp add: defined-lit-map)
          then have ∃ S'. cdclW-o S S'
            using cdclW-o.decide decide.intros ⟨l ∈ ?B⟩ no-strange-atm-def
            by (metis ⟨conflicting S = None⟩ 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 ¬ ?M ⊨a D and D ∈# ?N
      using ⟨¬?M ⊨asm ?N⟩ unfolding lits-of-def true-annots-def Ball-def by auto
    have atms-of D ⊆ atm-of ' (lits-of ?M)
      using ⟨D ∈# ?N⟩ unfolding ⟨atm-of ' (lits-of ?M) = atms-of-msu ?N⟩ atms-of-ms-def
      by (auto simp add: atms-of-def)
    then have a1: atm-of ' set-mset D ⊆ 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 ⟨atms-of D ⊆ atm-of ' (lits-of ?M)⟩ atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
      by (fastforce simp: total-over-set-def)
    then have ?M ⊨as CNot D
      using total-not-true-clss-true-clss-CNot ⟨¬ trail S ⊨a D⟩ 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 ⟨D ∈# init-clss S⟩ ⟨conflicting S = None⟩ ⟨trail S ⊨as CNot D⟩
          clauses-def full-cdclW-cp-not-any-negated-init-clss by auto
      qed
    qed
  }
  then have ?M ⊨asm ?N by blast
}
moreover {

```

```

assume  $\exists D L. \text{conflicting } S = \text{Some } (D + \{\#L\# \})$ 
then obtain  $D L$  where  $LD: \text{conflicting } S = \text{Some } (D + \{\#L\# \})$  and  $\text{lev-}L: \text{get-level } ?M L = ?k$ 
  by (metis (mono-tags) bex-msetE confl-k insert-DiffM2 multi-self-add-other-not-self
    union-eq-empty)
let  $?D = D + \{\#L\# \}$ 
have  $?D \neq \{\# \}$  by auto
have  $?M \models_{as} CNot ?D$  using confl LD unfolding cdclW-conflicting-def by auto
then have  $?M \neq []$  unfolding true-annots-def Ball-def true-annot-def true-cls-def by force
{ have  $M: ?M = \text{hd } ?M \# \text{tl } ?M$  using  $\langle ?M \neq [] \rangle$  list.collapse by fastforce
  assume marked: is-marked ( $\text{hd } ?M$ )
  then obtain  $k'$  where  $k': k' + 1 = ?k$ 
    using level-inv M unfolding cdclW-M-level-inv-def
    by (cases  $\text{hd } (\text{trail } S)$ ; cases  $\text{trail } S$ ) auto
  obtain  $L' l'$  where  $L': \text{hd } ?M = \text{Marked } L' l'$  using marked by (cases  $\text{hd } ?M$ ) auto
  have marked-hd-tl: get-all-levels-of-marked ( $\text{hd } (\text{trail } S) \# \text{tl } (\text{trail } S)$ )
     $= \text{rev } [1..<1 + \text{length } (\text{get-all-levels-of-marked } ?M)]$ 
    using level-inv lev-L M unfolding cdclW-M-level-inv-def  $M[\text{symmetric}]$ 
    by blast
  then have  $l'-\text{tl}: l' \# \text{get-all-levels-of-marked } (\text{tl } ?M)$ 
     $= \text{rev } [1..<1 + \text{length } (\text{get-all-levels-of-marked } ?M)]$  unfolding  $L'$  by simp
  moreover have  $\dots = \text{length } (\text{get-all-levels-of-marked } ?M)$ 
     $\# \text{rev } [1..<\text{length } (\text{get-all-levels-of-marked } ?M)]$ 
    using  $M \text{ Suc-le-mono calculation}$  by (fastforce simp add: upt.simps(2))
  finally have
     $l' = ?k$  and
     $g-r: \text{get-all-levels-of-marked } (\text{tl } (\text{trail } S))$ 
       $= \text{rev } [1..<\text{length } (\text{get-all-levels-of-marked } (\text{trail } S))]$ 
      using level-inv lev-L M unfolding cdclW-M-level-inv-def by auto
  have  $*$ :  $\bigwedge \text{list. no-dup list} \implies$ 
     $-L \in \text{lits-of list} \implies \text{atm-of } L \in \text{atm-of 'lits-of list}$ 
    by (metis atm-of-uminus imageI)
  have  $L' = -L$ 
    proof (rule ccontr)
      assume  $\neg ?thesis$ 
      moreover have  $-L \in \text{lits-of } ?M$  using confl LD unfolding cdclW-conflicting-def by auto
      ultimately have  $\text{get-level } (\text{hd } (\text{trail } S) \# \text{tl } (\text{trail } S)) L = \text{get-level } (\text{tl } ?M) L$ 
        using cdclW-M-level-inv-decomp(1)[OF level-inv] unfolding  $L'$  consistent-interp-def
        by (metis (no-types, lifting)  $L' M \text{ atm-of-eq-atm-of get-level-skip-beginning insert-iff}$ 
          lits-of-cons marked-lit.sel(1))

      moreover
        have  $\text{length } (\text{get-all-levels-of-marked } (\text{trail } S)) = ?k$ 
          using level-inv unfolding cdclW-M-level-inv-def by auto
        then have  $\text{Max } (\text{set } (0 \# \text{get-all-levels-of-marked } (\text{tl } (\text{trail } S)))) = ?k - 1$ 
          unfolding  $g-r$  by (auto simp add: Max-n-upt)
        then have  $\text{get-level } (\text{tl } ?M) L < ?k$ 
          using get-maximum-possible-level-ge-get-level[of tl ?M L]
          by (metis One-nat-def add.right-neutral add-Suc-right diff-add-inverse2
            get-maximum-possible-level-max-get-all-levels-of-marked  $k' \text{ le-imp-less-Suc}$ 
            list.simps(15))
        finally show False using lev-L M by auto
      qed
  have  $L: \text{hd } ?M = \text{Marked } (-L) ?k$  using  $\langle l' = ?k \rangle \langle L' = -L \rangle L'$  by auto

  have  $g-a-l: \text{get-all-levels-of-marked } ?M = \text{rev } [1..<1 + ?k]$ 

```

```

using level-inv lev-L M unfolding cdclW-M-level-inv-def by auto
have g-k: get-maximum-level (trail S) D ≤ ?k
  using get-maximum-possible-level-ge-get-maximum-level[of ?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 (trail S) D < ?k
proof (rule ccontr)
  assume  $\neg ?thesis$ 
  then have get-maximum-level (trail S) D = ?k using M g-k unfolding L by auto
  then obtain L' where  $L' \in \# D$  and L-k: get-level ?M L' = ?k
    using get-maximum-level-exists-lit[of ?k ?M D] unfolding k'[symmetric] by auto
  have  $L \neq L'$  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  $\neg ?thesis$ 
  then have get-level ?M L' = get-level (tl ?M) L'
    using M (L ≠ L') get-level-skip-beginning[of L' hd ?M tl ?M] unfolding L
    by (auto simp: atm-of-eq-atm-of)
  moreover have  $\dots < ?k$ 
proof –
  { assume a1: get-level (tl (trail S)) L' = backtrack-lvl S
    assume a2: rev (get-all-levels-of-marked (tl (trail S))) =
      [Suc 0..<backtrack-lvl S]
    have  $k' + \text{Suc } 0 = \text{backtrack-lvl } S$ 
      using k' by presburger
    then have False
      using a2 a1 by (metis (no-types) Max-n-upt Zero-neq-Suc add-diff-cancel-left'
        add-diff-cancel-right' diff-is-0-eq
        get-all-levels-of-marked-rev-eq-rev-get-all-levels-of-marked
        get-rev-level-less-max-get-all-levels-of-marked list.set(2) set-upt)
  }
  then show ?thesis
    using g-r get-rev-level-less-max-get-all-levels-of-marked[of rev (tl ?M) 0 L]
      l'-tl calculation[symmetric] g-a-l L-k
    by (auto simp: Max-n-upt cdclW-M-level-inv-def rev-swap[symmetric])
qed
finally show False using L-k by simp
qed
then have taut: tautology (D + {#L#})
  using  $\langle L' \in \# D \rangle$  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  $\neg ?M \models_{as} CNot ?D$ 
  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  $?M \models_{as} CNot ?D$ 
  using confl no-dup LD unfolding cdclW-conflicting-def by auto
ultimately show False by blast
qed
then have False
  using backtrack-no-decomp[OF - (get-level (trail S) L = backtrack-lvl S) - level-inv]
    LD alien termi by (metis cdclW-then-exists-cdclW-stgy-step level-inv)

```

```

}
moreover {
  assume  $\neg is\_marked$  (hd ?M)
  then obtain  $L' C$  where  $L' C$ : hd ?M = Propagated  $L' C$  by (cases hd ?M, auto)
  then have  $M$ : ?M = Propagated  $L' C \# tl$  ?M using  $\langle ?M \neq [] \rangle$  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  $-L' \notin \# ?D$ 
    then have False
      using bj[OF cdclW-bj.skip[OF skip-rule[OF -  $\langle -L' \notin \# ?D \rangle \langle ?D \neq \{\#\} \rangle$ , 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  $-L' \in \# ?D$ 
  then obtain  $D'$  where  $D'$ : ?D =  $D' + \{\#-L'\#\}$  by (metis insert-DiffM2)
  have  $g-r$ : get-all-levels-of-marked (Propagated  $L' C \# tl$  (trail  $S$ )))
    = rev [Suc 0..Suc (length (get-all-levels-of-marked (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 (Propagated  $L' C \# tl$  ?M)  $D' \leq ?k$ 
    using get-maximum-possible-level-ge-get-maximum-level[of Propagated  $L' C \# tl$  ?M]
    unfolding get-maximum-possible-level-max-get-all-levels-of-marked by auto
  then have get-maximum-level (Propagated  $L' C \# tl$  ?M)  $D' = ?k$ 
     $\vee$  get-maximum-level (Propagated  $L' C \# tl$  ?M)  $D' < ?k$ 
    using le-neq-implies-less by blast
  moreover {
    assume  $g-D'-k$ : get-maximum-level (Propagated  $L' C \# tl$  ?M)  $D' = ?k$ 
    have False
    proof -
      have  $f1$ : get-maximum-level (trail  $S$ )  $D' = backtrack-lvl$   $S$ 
        using  $M g-D'-k$  by auto
      have (trail  $S$ , init-clss  $S$ , learned-clss  $S$ , backtrack-lvl  $S$ , Some ( $D + \{\#L'\#\}$ ))
        = state  $S$ 
        by (metis (no-types) LD)
      then have cdclW-o  $S$  (update-conflicting (Some ( $D' \# \cup C'$ )) (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 (Propagated  $L' C \# tl$  ?M)  $D' < ?k$ 
  then have False
  proof -
    assume  $a1$ : get-maximum-level (Propagated  $L' C \# tl$  (trail  $S$ )))  $D' < backtrack-lvl$   $S$ 
    obtain  $mm :: 'v$  literal multiset and  $ll :: 'v$  literal where
       $f2$ : conflicting  $S = Some$  ( $mm + \{\#ll'\#\}$ )
      get-level (trail  $S$ )  $ll = backtrack-lvl$   $S$ 
      using LD (get-level (trail  $S$ )  $L = backtrack-lvl$   $S$ ) by blast
    then have  $f3$ : get-maximum-level (trail  $S$ )  $D' \leq get-level (trail  $S$ )  $ll$ 
      using  $M a1$  by force
  }
}$ 
```



```

    have lev-neq: get-level (trail S) ll  $\neq$  get-maximum-level (trail S) D'
      using f2 M calculation(2) by presburger
    have f1: trail S = Propagated L' C # tl (trail S)
      conflicting S = Some (D' + {#- L'#})
      using D' LD M by force+
    have f2: conflicting S = Some (mm + {#ll#})
      get-level (trail S) ll = backtrack-lvl S
      using f2 by force+
    have ll = - L'
      by (metis (no-types) D' LD lev-neq option.inject f2 f3 le-antisym
        get-maximum-level-ge-get-level insert-noteq-member)
    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.other cdclW-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 cdcl_W-stgy-tranclp-cdcl_W tranclp-trans)

lemma rtranclp-cdcl_W-stgy-rtranclp-cdcl_W:

cdcl_W-stgy^{**} S S' \implies cdcl_W^{**} S S'

using rtranclp-unfold[of cdcl_W-stgy S S'] tranclp-cdcl_W-stgy-tranclp-cdcl_W[of S S'] by auto

lemma cdcl_W-o-conflict-is-false-with-level-inv:

assumes

cdcl_W-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 (Propagated L (C + {#L#})) # M) D

= get-maximum-level M D

proof -

have $\forall a f L. ((a::'v) \in f \text{ ' } L) = (\exists l. (l::'v \text{ literal}) \in L \wedge a = f l)$

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) $\langle - L \notin \# D \rangle \langle L \notin \# D \rangle$ atm-of-eq-atm-of mem-set-mset-iff)

qed

{ **assume**

get-maximum-level (Propagated L (C + {#L#})) # M) D = backtrack-lvl S and

backtrack-lvl S > 0

then have D: get-maximum-level M D = backtrack-lvl S **unfolding** g-D **by** blast

then have ?case

using tr-S $\langle \text{backtrack-lvl S} > 0 \rangle$ get-maximum-level-exists-lit[of backtrack-lvl S M D] T

by auto

}

moreover {

assume [simp]: backtrack-lvl S = 0

have $\bigwedge L. \text{get-level M L} = 0$

proof -

fix L

have atm-of L \notin atm-of ' (lits-of M) \implies get-level M L = 0 **by** auto

```

    moreover {
      assume atm-of L ∈ atm-of ' (lits-of M)
      have g-r: get-all-levels-of-marked M = rev [Suc 0..<Suc (backtrack-lvl S)]
        using lev tr-S unfolding cdclW-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 M L = 0
        using get-maximum-possible-level-ge-get-level[of M L]
        unfolding get-maximum-possible-level-max-get-all-levels-of-marked by auto
    }
    ultimately show get-level M L = 0 by blast
  qed
  then have ?case using get-maximum-level-exists-lit-of-max-level[of D#∪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 = this(2) and T = this(5)
then obtain La where La ∈# D and get-level (Propagated L C' # M) La = backtrack-lvl S
  using skip confl-inv by auto
moreover
  have atm-of La ≠ atm-of L
  proof (rule ccontr)
    assume ¬ ?thesis
    then have La: La = L using ⟨La ∈# D⟩ ⟨- L ∉# D⟩ by (auto simp add: atm-of-eq-atm-of)
    have Propagated L C' # M ⊨as CNot D
      using conflicting tr-S D unfolding cdclW-conflicting-def by auto
    then have -L ∈ lits-of M
      using ⟨La ∈# D⟩ in-CNot-implies-uminus(2)[of D L 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 (Propagated L C' # M) La = get-level M La by auto
  ultimately show ?case using D 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 ∨ (∃ S'. propagate** S S' ∧ conflict S' T)*
using *assms* **by** *induction blast+*

lemma *rtrancp-cdcl_W-cp-propagate-confl*:

assumes *cdcl_W-cp** S T*
shows *propagate** S T ∨ (∃ S'. propagate** S S' ∧ conflict S' T)*
by *(simp add: assms rtrancp-cdcl_W-cp-propa-or-propa-confl)*

lemma *cdcl_W-cp-propagate-completeness*:

assumes *MN: set M ⊨_s set-mset N* **and**
cons: consistent-interp (set M) **and**
tot: total-over-m (set M) (set-mset N) **and**
lits-of (trail S) ⊆ set M **and**
init-clss S = N **and**
*propagate** S S'* **and**
learned-clss S = {#}

```

shows  $\text{length } (\text{trail } S) \leq \text{length } (\text{trail } S') \wedge \text{lits-of } (\text{trail } S') \subseteq \text{set } M$ 
using assms(6,4,5,7)
proof (induction rule: rtrancpl-induct)
  case base
  then show ?case by auto
next
  case (step Y Z)
  note st = this(1) and propa = this(2) and IH = this(3) and lits' = this(4) and NS = this(5) and
    learned = this(6)
  then have len:  $\text{length } (\text{trail } S) \leq \text{length } (\text{trail } Y)$  and LM:  $\text{lits-of } (\text{trail } Y) \subseteq \text{set } M$ 
    by blast+

obtain M' N' U k C L where
  Y: state Y = (M', N', U, k, None) and
  Z: state Z = (Propagated L (C + {#L#}) # M', N', U, k, None) and
  C: C + {#L#}  $\in \# \text{ clauses } Y$  and
  M'-C: M'  $\models_{\text{as}} C \text{Not } C$  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  $\models_s C \text{Not } C$ 
  using M'-C LM Y unfolding true-annots-def Ball-def true-annot-def true-clss-def true-cl-def
  by force
moreover
  have set M  $\models C + \{ \#L\# \}$ 
  using MN C learned Y unfolding true-clss-def clauses-def
  by (metis NS  $\langle \text{init-clss } S = \text{init-clss } Y \rangle \langle \text{learned-clss } Y = \{ \# \} \rangle$  add.right-neutral
    mem-set-mset-iff)
  ultimately have L  $\in \text{set } M$  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  $\models_s \text{set-mset } N$ 
  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:  $\text{lits-of } (\text{trail } S) \subseteq \text{set } M$ 
  shows  $\exists S'. \text{propagate}^{**} S S' \wedge \text{full cdcl}_W\text{-cp } S S'$ 
proof –
  obtain S' where full: full cdclW-cp S S'
  using always-exists-full-cdclW-cp-step alien by blast
  then consider (propa) propagate** S S'
  | (confl)  $\exists X. \text{propagate}^{**} S X \wedge \text{conflict } X S'$ 
  using rtrancpl-cdclW-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 ∈# init-clss X + learned-clss X and
  Not-E: trail X ⊨as CNot E
  using Xconf by (auto simp add: conflict.simps clauses-def)
have lits-of (trail X) ⊆ set M
  using cdclW-cp-propagate-completeness[OF assms(1-3) lits - X learned] learned by auto
then have MNE: set M ⊨s CNot E
  using Not-E
  by (fastforce simp add: true-annots-def true-annot-def true-clss-def true-clss-def)
have ¬ set M ⊨s 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 $cdcl_W\text{-}cp^{**} \text{ ?}S \text{ ?}S' \implies \exists M. \text{ trail ?}S' = M @ \text{ trail ?}S \wedge (\forall l \in \text{set } M. \neg \text{is-marked } l)$

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 $\implies cdcl_W\text{-}M\text{-level-inv } S \implies T \sim \text{delete-trail-and-rebuild } (\text{trail } T) S$*

proof (induction rule: rtrancp-induct)

case base

then show ?case unfolding state-eq-def by (auto simp: cdcl_W-M-level-inv-decomp state-access-simp)

next

case (step T U) note IH=this(3)[OF this(4)]

moreover have cdcl_W-M-level-inv U

using rtrancp-cdcl_W-consistent-inv ⟨propagate** S T⟩ ⟨propagate T U⟩

rtrancp-mono[of propagate cdcl_W] cdcl_W-cp-consistent-inv propagate'

rtrancp-propagate-is-rtrancp-cdcl_W step.prem by blast

then have no-dup (trail U) unfolding cdcl_W-M-level-inv-def by auto

ultimately show ?case using ⟨propagate T U⟩ unfolding state-eq-def

by (fastforce simp: state-access-simp)

qed

lemma *cdcl_W-stgy-strong-completeness-n:*

assumes

MN: set M ⊨_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) ⊆ atms-of-msu N and

distM: distinct M and

length: n ≤ 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 ($\text{induction } n$)
case 0
have $\text{update-backtrack-lvl } 0 (\text{append-trail } (\text{rev } []) (\text{init-state } N)) \sim \text{init-state } N$
by ($\text{auto simp: state-eq-def simp del: state-simp}$)
moreover have
 $0 \leq \text{length } []$ **and**
 $\text{lits-of } [] \subseteq \text{set } M$ **and**
 $\text{cdcl}_W\text{-stgy}^{**} (\text{init-state } N) (\text{init-state } N)$
and $\text{no-dup } []$
by ($\text{auto simp: state-eq-def simp del: state-simp}$)
ultimately show ?case **using** state-eq-sym **by** blast
next
case ($\text{Suc } n$) **note** $IH = \text{this}(1)$ **and** $n = \text{this}(2)$
then obtain $M' k S$ **where**
 $l\text{-}M': \text{length } M' \geq n$ **and**
 $M': \text{lits-of } M' \subseteq \text{set } M$ **and**
 $n\text{-d}[\text{simp}]: \text{no-dup } M'$ **and**
 $S: S \sim \text{update-backtrack-lvl } k (\text{append-trail } (\text{rev } M') (\text{init-state } N))$ **and**
 $st: \text{cdcl}_W\text{-stgy}^{**} (\text{init-state } N) S$
by auto
have
 $M: \text{cdcl}_W\text{-}M\text{-level-inv } S$ **and**
 $\text{alien: no-strange-atm } S$
using $\text{rtranclp-cdcl}_W\text{-consistent-inv}[OF \text{ rtranclp-cdcl}_W\text{-stgy-rtranclp-cdcl}_W[OF st]]$
 $\text{rtranclp-cdcl}_W\text{-no-strange-atm-inv}[OF \text{ rtranclp-cdcl}_W\text{-stgy-rtranclp-cdcl}_W[OF st]]$
 S **unfolding** $\text{state-eq-def cdcl}_W\text{-}M\text{-level-inv-def no-strange-atm-def}$ **by** auto
{ assume $\text{no-step: } \neg \text{no-step}$ **propagate** S

obtain S' **where** $S': \text{propagate}^{**} S S'$ **and** $\text{full: full cdcl}_W\text{-cp } S S'$
using $\text{completeness-is-a-full1-propagation}[OF \text{ assms}(1-3), \text{ of } S]$ $\text{alien } M' S$
by ($\text{auto simp: state-access-simp}$)
have $\text{lev: cdcl}_W\text{-}M\text{-level-inv } S'$
using $M S' \text{ rtranclp-cdcl}_W\text{-consistent-inv rtranclp-propagate-is-rtranclp-cdcl}_W$ **by** blast
then have $n\text{-d}'[\text{simp}]: \text{no-dup } (\text{trail } S')$
unfolding $\text{cdcl}_W\text{-}M\text{-level-inv-def}$ **by** auto
have $\text{length } (\text{trail } S) \leq \text{length } (\text{trail } S') \wedge \text{lits-of } (\text{trail } S') \subseteq \text{set } M$
using $S' \text{ full cdcl}_W\text{-cp-propagate-completeness}[OF \text{ assms}(1-3), \text{ of } S]$ $M' S$
by ($\text{auto simp: state-access-simp}$)
moreover
have $\text{full: full1 cdcl}_W\text{-cp } S S'$
using $\text{full no-step no-step-cdcl}_W\text{-cp-no-conflict-no-propagate}(2)$ **unfolding** $\text{full1-def full-def}$
 rtranclp-unfold **by** blast
then have $\text{cdcl}_W\text{-stgy } S S'$ **by** ($\text{simp add: cdcl}_W\text{-stgy.conflict'}$)
moreover
have $\text{propa: propagate}^{++} S S'$ **using** $S' \text{ full unfolding full1-def}$ **by** ($\text{metis rtranclpD tranclpD}$)
have $\text{trail } S = M'$ **using** S **by** ($\text{auto simp: state-access-simp}$)
with propa have $\text{length } (\text{trail } S') > n$
using $l\text{-}M' \text{ propa}$ **by** ($\text{induction rule: tranclp.induct}$) auto

```

moreover
  have  $stS'$ :  $cdcl_W\text{-}stgy^{**}$  ( $init\text{-}state\ N$ )  $S'$ 
    using  $st\ cdcl_W\text{-}stgy.conflict'$ [ $OF\ full$ ] by  $auto$ 
  then have  $init\text{-}clss\ S' = N$  using  $stS'\ rtranclp\text{-}cdcl_W\text{-}stgy\text{-}no\text{-}more\text{-}init\text{-}clss$  by  $fastforce$ 
moreover
  have
     $[simp]:learned\text{-}clss\ S' = \{\#\}$  and
     $[simp]: init\text{-}clss\ S' = init\text{-}clss\ S$  and
     $[simp]: conflicting\ S' = None$ 
    using  $trancpl\text{-}into\text{-}rtranclp[OF\ \langle propagate^{++}\ S\ S'\rangle]\ S$ 
     $rtranclp\text{-}propagate\text{-}is\text{-}update\text{-}trail[of\ S\ S']\ S\ M$  unfolding  $state\text{-}eq\text{-}def$ 
    by ( $auto\ simp: state\text{-}access\text{-}simp$ )
  have  $S\text{-}S'$ :  $S' \sim update\text{-}backtrack\text{-}lvl\ (backtrack\text{-}lvl\ S')$ 
    ( $append\text{-}trail\ (rev\ (trail\ S'))\ (init\text{-}state\ N)$ ) using  $S$ 
    by ( $auto\ simp: state\text{-}eq\text{-}def\ state\text{-}access\text{-}simp\ simp\ del: state\text{-}simp$ )
  have  $cdcl_W\text{-}stgy^{**}$  ( $init\text{-}state\ (init\text{-}clss\ S')$ )  $S'$ 
    apply ( $rule\ rtranclp.rtrancl\text{-}into\text{-}rtrancl$ )
    using  $st$  unfolding ( $init\text{-}clss\ S' = N$ ) apply  $simp$ 
    using  $\langle cdcl_W\text{-}stgy\ S\ S'\rangle$  by  $simp$ 
  ultimately have  $?case$ 
    apply –
    apply ( $rule\ exI[of\ \text{-}\ trail\ S']$ ,  $rule\ exI[of\ \text{-}\ backtrack\text{-}lvl\ S']$ ,  $rule\ exI[of\ \text{-}\ S']$ )
    using  $S\text{-}S'$  by ( $auto\ simp: state\text{-}eq\text{-}def\ simp\ del: state\text{-}simp$ )
}
moreover {
  assume  $no\text{-}step: no\text{-}step\ propagate\ S$ 
  have  $?case$ 
    proof ( $cases\ length\ M' \geq Suc\ n$ )
      case  $True$ 
        then show  $?thesis$  using  $l\text{-}M'\ M'\ st\ M\ alien\ S$  by  $fastforce$ 
      next
        case  $False$ 
          then have  $n'$ :  $length\ M' = n$  using  $l\text{-}M'$  by  $auto$ 
          have  $no\text{-}confl$ :  $no\text{-}step\ conflict\ S$ 
          proof –
            { fix  $D$ 
              assume  $D \in \# N$  and  $M' \models_{as} CNot\ D$ 
              then have  $set\ M \models D$  using  $MN$  unfolding  $true\text{-}clss\text{-}def$  by  $auto$ 
              moreover have  $set\ M \models_s CNot\ D$ 
                using ( $M' \models_{as} CNot\ D$ )  $M'$ 
                by ( $metis\ le\text{-}iff\text{-}sup\ true\text{-}annots\text{-}true\text{-}cls\ true\text{-}clss\text{-}union\text{-}increase$ )
              ultimately have  $False$  using  $cons\ consistent\text{-}CNot\text{-}not$  by  $blast$ 
            }
          then show  $?thesis$  using  $S$  by ( $auto\ simp: conflict.simps\ true\text{-}clss\text{-}def\ state\text{-}access\text{-}simp$ )
        }
    qed
  have  $lenM$ :  $length\ M = card\ (set\ M)$  using  $distM$  by ( $induction\ M$ )  $auto$ 
  have  $no\text{-}dup\ M'$  using  $S\ M$  unfolding  $cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}def$  by  $auto$ 
  then have  $card\ (lits\text{-}of\ M') = length\ M'$ 
    by ( $induction\ M'$ ) ( $auto\ simp\ add: lits\text{-}of\text{-}def\ card\text{-}insert\text{-}if$ )
  then have  $lits\text{-}of\ M' \subset set\ M$ 
    using  $n\ M'\ n'\ lenM$  by  $auto$ 
  then obtain  $m$  where  $m$ :  $m \in set\ M$  and  $undef\text{-}m$ :  $m \notin lits\text{-}of\ M'$  by  $auto$ 
  moreover have  $undef$ :  $undefined\text{-}lit\ M'\ m$ 
    using  $M'\ Marked\text{-}Propagated\text{-}in\text{-}iff\text{-}in\text{-}lits\text{-}of\ calculation(1,2)\ cons$ 
     $consistent\text{-}interp\text{-}def$  by  $blast$ 

```

```

moreover have atm-of  $m \in \text{atms-of-msu } (\text{init-clss } S)$ 
  using atm-incl calculation  $S$  by (auto simp: state-access-simp)
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 simp: state-access-simp)
let  $?S' = \text{cons-trail } (\text{Marked } m \text{ } (k+1)) \text{ } (\text{incr-lvl } S)$ 
have lits-of (trail  $?S'$ )  $\subseteq \text{set } M$  using  $m$   $M'$   $S$  undef by (auto simp: state-access-simp)
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 simp: state-access-simp)
have cdclW-M-level-inv  $?S'$ 
  using  $M$  dec rtranclp-mono[of decide cdclW] by (meson cdclW-consistent-inv decide other)
then have lev'': cdclW-M-level-inv  $S''$ 
  using  $S''$  rtranclp-cdclW-consistent-inv rtranclp-propagate-is-rtranclp-cdclW by blast
then have n-d'': no-dup (trail  $S''$ )
  unfolding cdclW-M-level-inv-def by auto
have length (trail  $?S'$ )  $\leq \text{length } (\text{trail } S'') \wedge \text{lits-of } (\text{trail } S'') \subseteq \text{set } M$ 
  using  $S''$  full cdclW-cp-propagate-completeness[OF assms(1-3), of  $?S' S''$ ]  $m$   $M'$   $S$  undef
  by (simp add: state-access-simp)
then have Suc  $n \leq \text{length } (\text{trail } S'') \wedge \text{lits-of } (\text{trail } S'') \subseteq \text{set } M$ 
  using l- $M'$   $S$  undef by (auto simp: state-access-simp)
moreover
  have cdclW-M-level-inv (cons-trail (Marked  $m$  (Suc (backtrack-lvl  $S$ )))
    (update-backtrack-lvl (Suc (backtrack-lvl  $S$ ))  $S$ ))
    using  $S$  cdclW-M-level-inv (cons-trail (Marked  $m$  ( $k + 1$ )) (incr-lvl  $S$ )) by auto
  then have  $S''$ :  $S'' \sim \text{update-backtrack-lvl } (\text{backtrack-lvl } S'')$ 
    (append-trail (rev (trail  $S''$ )) (init-state  $N$ ))
    using rtranclp-propagate-is-update-trail[OF  $S''$ ]  $S$  undef n-d'' lev''
    by (auto simp del: state-simp simp: state-eq-def state-access-simp)
  then have cdclW-stgy** (init-state  $N$ )  $S''$ 
    using cdclW-stgy.intros(2)[OF decide[OF dec] - full] no-step no-confl st
    by (auto simp: cdclW-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  $M \models_s \text{set-mset } N$ 
and cons: consistent-interp (set  $M$ )
and tot: total-over-m (set  $M$ ) (set-mset  $N$ )
and atm-incl: atm-of ' (set  $M$ )  $\subseteq \text{atms-of-msu } N$ 
and distM: distinct  $M$ 

```

shows

```

 $\exists M' k S.$ 
  lits-of  $M' = \text{set } M \wedge$ 
   $S \sim \text{update-backtrack-lvl } k \text{ } (\text{append-trail } (\text{rev } M') \text{ } (\text{init-state } N)) \wedge$ 
  cdclW-stgy** (init-state  $N$ )  $S \wedge$ 
  final-cdclW-state  $S$ 

```

proof —


```

from cdclW-stgy-strong-completeness-n[OF assms, of length M]
obtain M' k T where
  l: length M ≤ length M' and
  M'-M: lits-of M' ⊆ set M and
  no-dup: no-dup M' and
  T: T ~ update-backtrack-lvl k (append-trail (rev M') (init-state N)) and
  st: cdclW-stgy** (init-state N) T
  by auto
have card (set M) = length M using distM by (simp add: distinct-card)
moreover
  have cdclW-M-level-inv T
    using rtrancpl-cdclW-stgy-consistent-inv[OF st] T by auto
  then have card (set ((map (λl. atm-of (lit-of l)) M')) = length M'
    using distinct-card no-dup by fastforce
moreover have card (lits-of M') = card (set ((map (λl. 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) ≤ 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' ⊨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 simp: state-access-simp)
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-confl* (*S::'st*) ≡
 ($\forall M K i M' D. M' @ \text{Marked } K i \# M = \text{trail } S \longrightarrow D \in \# \text{ clauses } S$
 $\longrightarrow \neg M \models_{as} CNot D$)

lemma *no-smaller-confl-init-sate[simp]*:
no-smaller-confl (init-state N) unfolding no-smaller-confl-def by auto

lemma *cdcl_W-o-no-smaller-confl-inv*:
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**
smaller: *no-smaller-confl S* **and**
no-f: *no-clause-is-false S*
shows *no-smaller-confl S'*
using *assms(1,2) unfolding no-smaller-confl-def*
proof (*induct rule: cdcl_W-o-induct-lev2*)
case (*decide L T*) **note** *confl = this(1)* **and** *undef = this(2)* **and** *T = 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  $T \text{ undef by (cases } M'') \text{ auto}$ 
moreover {
  assume  $tl \ M'' @ \text{Marked } K \ i \ \# \ M' = \text{trail } S$ 
  then have  $\neg M' \models_{as} CNot \ Da$ 
    using  $D \ T \text{ undef no-f confl smaller unfolding no-smaller-confl-def smaller by fastforce}$ 
  }
moreover {
  assume  $\text{Marked } K \ i \ \# \ M' = \text{Marked } L \ (\text{backtrack-lvl } S + 1) \ \# \ \text{trail } S$ 
  then have  $\neg M' \models_{as} CNot \ Da$  using  $\text{no-f } D \text{ confl } T \text{ by auto}$ 
  }
ultimately show  $\neg M' \models_{as} CNot \ Da$  by fast
qed
next
  case resolve
    then show  $?case$  using  $\text{smaller no-f max-lev unfolding no-smaller-confl-def by auto}$ 
  next
    case skip
      then show  $?case$  using  $\text{smaller no-f max-lev unfolding no-smaller-confl-def by auto}$ 
  next
    case  $(\text{backtrack } K \ i \ M1 \ M2 \ L \ D \ T)$  note  $\text{decomp} = \text{this}(1)$  and  $\text{confl} = \text{this}(3)$  and  $\text{undef} = \text{this}(6)$ 
      and  $T = \text{this}(7)$ 
    obtain  $c$  where  $M: \text{trail } S = c @ M2 @ \text{Marked } K \ (i+1) \ \# \ M1$ 
      using  $\text{decomp by auto}$ 

show  $?case$ 
proof  $(\text{intro allI impI})$ 
  fix  $M \ ia \ K' \ M' \ Da$ 
  assume  $M' @ \text{Marked } K' \ ia \ \# \ M = \text{trail } T$ 
  then have  $tl \ M' @ \text{Marked } K' \ ia \ \# \ M = M1$ 
    using  $T \text{ decomp undef lev by (cases } M') \text{ (auto simp: cdcl}_W\text{-M-level-inv-decomp)}$ 
  assume  $D: Da \in \# \text{ clauses } T$ 
  moreover{
    assume  $Da \in \# \text{ clauses } S$ 
    then have  $\neg M \models_{as} CNot \ Da$  using  $\langle tl \ M' @ \text{Marked } K' \ ia \ \# \ M = M1 \rangle M \text{ confl undef smaller}$ 
      unfolding no-smaller-confl-def by auto
  }
  moreover {
    assume  $Da: Da = D + \{\#L\# \}$ 
    have  $\neg M \models_{as} CNot \ Da$ 
    proof  $(\text{rule ccontr})$ 
      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  $UnI2 \ \langle tl \ M' @ \text{Marked } K' \ ia \ \# \ M = M1 \rangle$ 
        by auto
      moreover
        have  $\text{backtrack } S$ 
         $(\text{cons-trail } (\text{Propagated } L \ (D + \{\#L\# \}))$ 
         $(\text{reduce-trail-to } M1 \ (\text{add-learned-cls } (D + \{\#L\# \}))$ 
         $(\text{update-backtrack-lvl } i \ (\text{update-conflicting } None \ S))))$ 
        using  $\text{backtrack.intros[of } S] \text{ backtrack.hyps}$ 
    
```

```

    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 None 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  $\langle Da = D + \{ \#L\# \} \implies \neg M \models_{as} CNot\ Da \rangle$  decomp lev
  unfolding cdclW-M-level-inv-def by fastforce
qed
qed

```

lemma *conflict-no-smaller-conflict-inv*:
 assumes *conflict* S S'
 and *no-smaller-conflict* S
 shows *no-smaller-conflict* S'
 using *assms* unfolding *no-smaller-conflict-def* by fastforce

lemma *propagate-no-smaller-conflict-inv*:
 assumes *propagate*: *propagate* S S'
 and *n-l*: *no-smaller-conflict* S
 shows *no-smaller-conflict* S'
 unfolding *no-smaller-conflict-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, None) and
 S': state S' = (Propagated L (C + {#L#})) # M, N, U, k, None) 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 $\neg M' \models_{as} CNot\ D$
 using $\langle D \in \# \text{ clauses } S' \rangle$ *n-l* S S' *clauses-def* unfolding *no-smaller-conflict-def* by auto
 then show $\neg M' \models_{as} CNot\ D$ by auto
qed

lemma *cdcl_W-cp-no-smaller-conflict-inv*:
 assumes *propagate*: *cdcl_W-cp* S S'
 and *n-l*: *no-smaller-conflict* S
 shows *no-smaller-conflict* S'
 using *assms*
proof (induct rule: *cdcl_W-cp.induct*)
 case (*conflict'* S S')

then show ?case using conflict-no-smaller-confl-inv[of S S'] by blast
 next
 case (propagate' S S')
 then show ?case using propagate-no-smaller-confl-inv[of S S'] by fastforce
 qed

lemma rtrancp-cdcl_W-cp-no-smaller-confl-inv:

assumes propagate: cdcl_W-cp^{**} S S'
 and n-l: no-smaller-confl S
 shows no-smaller-confl S'
 using assms

proof (induct rule: rtrancp-induct)

case base
 then show ?case by simp

next

case (step S' S'')
 then show ?case using cdcl_W-cp-no-smaller-confl-inv[of S' S''] by fast
 qed

lemma trancp-cdcl_W-cp-no-smaller-confl-inv:

assumes propagate: cdcl_W-cp⁺⁺ S S'
 and n-l: no-smaller-confl S
 shows no-smaller-confl S'
 using assms

proof (induct rule: trancp.induct)

case (r-into-tranc S S')
 then show ?case using cdcl_W-cp-no-smaller-confl-inv[of S S'] by blast

next

case (tranc-into-tranc S S' S'')
 then show ?case using cdcl_W-cp-no-smaller-confl-inv[of S' S''] by fast
 qed

lemma full-cdcl_W-cp-no-smaller-confl-inv:

assumes full cdcl_W-cp S S'
 and n-l: no-smaller-confl S
 shows no-smaller-confl S'
 using assms unfolding full-def
 using rtrancp-cdcl_W-cp-no-smaller-confl-inv[of S S'] by blast

lemma full1-cdcl_W-cp-no-smaller-confl-inv:

assumes full1 cdcl_W-cp S S'
 and n-l: no-smaller-confl S
 shows no-smaller-confl S'
 using assms unfolding full1-def
 using trancp-cdcl_W-cp-no-smaller-confl-inv[of S S'] by blast

lemma cdcl_W-stgy-no-smaller-confl-inv:

assumes cdcl_W-stgy S S'
 and n-l: no-smaller-confl S
 and conflict-is-false-with-level S
 and cdcl_W-M-level-inv S
 shows no-smaller-confl S'
 using assms

proof (induct rule: cdcl_W-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 (trail S) L = backtrack-lvl S))
shows ∀ D ∈# init-clss S' + learned-clss S'. trail S' ⊨as CNot D
  → (∃ L. L ∈# D ∧ get-level (trail S') L = backtrack-lvl S')
using assms by auto

```

lemma *is-conflicting-exists-conflict:*

```

assumes ¬(∀ D ∈# init-clss S' + learned-clss S'. ¬ trail S' ⊨as CNot D)
and conflicting S' = None
shows ∃ S''. 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
  cdclW-o S S' and
  lev: cdclW-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-conflict S
shows no-clause-is-false S'
  ∨ (conflicting S' = None
    → (∀ D ∈# clauses S'. trail S' ⊨as CNot D
      → (∃ L. L ∈# D ∧ get-level (trail S') L = backtrack-lvl S'))))
using assms(1,2)

```

proof (induct rule: cdcl_W-o-induct-lev2)

```

case (decide L T) note S = this(1) and undef = this(2) and T = this(4)

```

show ?case

proof (rule HOL.disjI2, clarify)

fix D

assume D: D ∈# clauses T and M-D: trail T ⊨_{as} CNot D

let ?M = trail S

let ?M' = trail T

let ?k = backtrack-lvl S

have ¬?M ⊨_{as} CNot D

using no-f D S T undef by auto

have -L ∈# D

proof (rule ccontr)

assume ¬ ?thesis

have ?M ⊨_{as} CNot D

unfolding true-annots-def Ball-def true-annot-def CNot-def true-clss-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  $M-D$   $x$   $T$  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  $\text{False}$  using  $\langle \neg ?M \models_{as} CNot D \rangle$  by auto
qed
have atm-of  $L \notin \text{atm-of } \langle \text{ lits-of } ?M \rangle$ 
  using undef defined-lit-map unfolding lits-of-def by fastforce
then have get-level (Marked  $L$  ( $?k + 1$ )  $\#$   $?M$ )  $(-L) = ?k + 1$  by simp
then show  $\exists La. La \in \# D \wedge \text{ get-level } ?M' La = \text{ backtrack-lvl } T$ 
  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 = this(1) and undef = this(6) and  $T = \text{this}(7)$ 
show  $?case$ 
proof (rule HOL.disjI2, clarify)
  fix  $Da$ 
  assume  $Da: Da \in \# \text{ clauses } T$ 
  and  $M-D: \text{ trail } T \models_{as} CNot Da$ 
  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: cdclW-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  $lev': \text{ cdcl}_W\text{-M-level-inv } T$ 
  using cdclW-consistent-inv lev other by blast
  then have  $- L \notin \text{ lits-of } M1$ 
  unfolding cdclW-M-level-inv-def lits-of-def
  proof -
  have consistent-interp (lits-of (trail  $S$ ))  $\wedge$  no-dup (trail  $S$ )
     $\wedge$  backtrack-lvl  $S = \text{length}$  (get-all-levels-of-marked (trail  $S$ ))
     $\wedge$  get-all-levels-of-marked (trail  $S$ )
    = rev [ $1..<1 + \text{length}$  (get-all-levels-of-marked (trail  $S$ ))]
  using lev cdclW-M-level-inv-def by blast
  then show  $- L \notin \text{ lit-of } \langle \text{ set } M1 \rangle$ 
  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)
    cdclW.backtrack-lit-skipped cdclW-axioms decomp lits-of-def)
  qed
{ assume  $Da \in \# \text{ clauses } S$ 
  then have  $\neg M1 \models_{as} CNot Da$  using no-l  $M$  unfolding no-smaller-conf-def by auto

```

```

}
moreover {
  assume  $Da: Da = D + \{\#L\# \}$ 
  have  $\neg M1 \models_{as} CNot\ Da$  using  $\langle -\ L \notin lits\text{-}of\ M1 \rangle$  unfolding  $Da$  by  $simp$ 
}
ultimately have  $\neg M1 \models_{as} CNot\ Da$ 
  using  $Da\ T\ undef\ decomp\ lev$  by  $(fastforce\ simp: cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}decomp)$ 
then have  $-L \in\# Da$ 
  using  $M\text{-}D\ \langle -\ L \notin lits\text{-}of\ M1 \rangle$  in  $CNot\text{-}implies\text{-}uminus(2)$ 
   $true\text{-}annots\text{-}CNot\text{-}lit\text{-}of\text{-}notin\text{-}skip\ T$  unfolding  $tr\text{-}T$ 
  by  $(smt\ insert\text{-}iff\ lits\text{-}of\text{-}cons\ marked\text{-}lit.sel(2))$ 
have  $g\text{-}M1: get\text{-}all\text{-}levels\text{-}of\text{-}marked\ M1 = rev\ [1..<i+1]$ 
  using  $lev\ lev'\ T\ decomp\ undef$  unfolding  $cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}def$  by  $auto$ 
have  $no\text{-}dup\ (Propagated\ L\ (D + \{\#L\# \}) \# M1)$ 
  using  $lev\ lev'\ T\ decomp\ undef$  unfolding  $cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}def$  by  $auto$ 
then have  $L: atm\text{-}of\ L \notin atm\text{-}of\ 'lits\text{-}of\ M1$  unfolding  $lits\text{-}of\text{-}def$  by  $auto$ 
have  $get\text{-}level\ (Propagated\ L\ ((D + \{\#L\# \})) \# M1)\ (-L) = i$ 
  using  $get\text{-}level\text{-}get\text{-}rev\text{-}level\text{-}get\text{-}all\text{-}levels\text{-}of\text{-}marked[OF\ L,$ 
   $of\ [Propagated\ L\ ((D + \{\#L\# \}))]]$ 
  by  $(simp\ add: g\text{-}M1\ split: if\text{-}splits)$ 
then show  $\exists La. La \in\# Da \wedge get\text{-}level\ (trail\ T)\ La = backtrack\text{-}lvl\ T$ 
  using  $\langle -L \in\# Da \rangle\ T\ decomp\ undef\ lev$  by  $(auto\ simp: cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}def)$ 
qed
qed

```

lemma $full1\text{-}cdcl_W\text{-}cp\text{-}exists\text{-}conflict\text{-}decompose$:

```

assumes  $confl: \exists D \in\# clauses\ S. trail\ S \models_{as} CNot\ D$ 
and  $full: full\ cdcl_W\text{-}cp\ S\ U$ 
and  $no\text{-}confl: conflicting\ S = None$ 
shows  $\exists T. propagate^{**}\ S\ T \wedge conflict\ T\ U$ 
proof –
  consider  $(propa)\ propagate^{**}\ S\ U$ 
  |  $(confl)\ T$  where  $propagate^{**}\ S\ T$  and  $conflict\ T\ U$ 
  using  $full$  unfolding  $full\text{-}def$  by  $(blast\ dest: rtranclp\text{-}cdcl_W\text{-}cp\text{-}propa\text{-}or\text{-}propa\text{-}confl)$ 
then show  $?thesis$ 
  proof  $cases$ 
  case  $confl$ 
  then show  $?thesis$  by  $blast$ 
next
  case  $propa$ 
  then have  $conflicting\ U = None$ 
  using  $no\text{-}confl$  by  $induction\ auto$ 
  moreover have  $[simp]: learned\text{-}clss\ U = learned\text{-}clss\ S$  and
   $[simp]: init\text{-}clss\ U = init\text{-}clss\ S$ 
  using  $propa$  by  $induction\ auto$ 
  moreover
  obtain  $D$  where  $D: D \in\# clauses\ U$  and
   $trS: trail\ S \models_{as} CNot\ D$ 
  using  $confl\ clauses\text{-}def$  by  $auto$ 
  obtain  $M$  where  $M: trail\ U = M @ trail\ S$ 
  using  $full\ rtranclp\text{-}cdcl_W\text{-}cp\text{-}dropWhile\text{-}trail$  unfolding  $full\text{-}def$  by  $meson$ 
  have  $tr\text{-}U: trail\ U \models_{as} CNot\ D$ 
  apply  $(rule\ true\text{-}annots\text{-}mono)$ 
  using  $trS$  unfolding  $M$  by  $simp\text{-}all$ 
  have  $\exists V. conflict\ U\ V$ 

```

```

    using (conflicting U = None) 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 conf:  $\exists D \in \# \text{clauses } S. \text{trail } S \models_{\text{as}} \text{CNot } D$ 
  and full: full cdclW-cp S U
  and no-conf: conflicting S = None
  shows  $\exists T D. \text{propagate}^{**} S T \wedge \text{conflict } T U$ 
     $\wedge \text{trail } T \models_{\text{as}} \text{CNot } D \wedge \text{conflicting } U = \text{Some } D \wedge D \in \# \text{clauses } S$ 

```

```

proof -
  obtain T where propa: propagate** S T and conf: conflict T U
    using full1-cdclW-cp-exists-conflict-decompose[OF assms] by blast
  have p: learned-clss T = learned-clss S init-clss T = init-clss S
    using propa by induction auto
  have c: learned-clss U = learned-clss T init-clss U = init-clss T
    using conf by induction auto
  obtain D where trail T  $\models_{\text{as}} \text{CNot } D \wedge \text{conflicting } U = \text{Some } D \wedge D \in \# \text{clauses } S$ 
    using conf p c by (fastforce simp: clauses-def)
  then show ?thesis
    using propa conf by blast
qed

```

```

lemma cdclW-stgy-no-smaller-conf:
  assumes cdclW-stgy S S'
  and n-l: no-smaller-conf S
  and conflict-is-false-with-level S
  and cdclW-M-level-inv S
  and no-clause-is-false S
  and distinct-cdclW-state S
  and cdclW-conflicting S
  shows no-smaller-conf S'
  using assms
proof (induct rule: cdclW-stgy.induct)
  case (conflict' S')
  show no-smaller-conf S'
    using conflict'.hyps conflict'.prems(1) full1-cdclW-cp-no-smaller-conf-inv 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
  show no-smaller-conf S''
    using cdclW-stgy-no-smaller-conf-inv[OF cdclW-stgy.other'[OF other'.hyps(1-3)]]
      other'.prems(1-3) by blast
qed

```

```

lemma cdclW-stgy-ex-lit-of-max-level:
  assumes cdclW-stgy S S'
  and n-l: no-smaller-conf S
  and conflict-is-false-with-level S
  and cdclW-M-level-inv S
  and no-clause-is-false S

```



```

and distinct-cdclW-state  $S$ 
and cdclW-conflicting  $S$ 
shows conflict-is-false-with-level  $S'$ 
using assms
proof (induct rule: cdclW-stgy.induct)
case (conflict'  $S'$ )
have no-smaller-confl  $S'$ 
  using conflict'.hyps conflict'.prems(1) full1-cdclW-cp-no-smaller-confl-inv by blast
moreover have conflict-is-false-with-level  $S'$ 
  using conflict'.hyps conflict'.prems(2-4)
  rtrancpl-cdclW-co-conflict-ex-lit-of-max-level[of S S']
  unfolding full-def full1-def rtrancpl-unfold by presburger
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  $S'$ 
   $\vee$  (conflicting  $S' = \text{None}$   $\longrightarrow$  ( $\forall D \in \# \text{clauses } S'. \text{trail } S' \models_{\text{as}} \text{CNot } D$ 
 $\longrightarrow$  ( $\exists L. L \in \# D \wedge \text{get-level}(\text{trail } S') L = \text{backtrack-lvl } S')$ ))
  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  $S' = \text{None}$ 
    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 rtrancpl-cdclW-co-conflict-ex-lit-of-max-level[of S' S''] lev' (no-clause-is-false S')
      by blast
  }
  moreover
  {
    assume c: conflicting  $S' \neq \text{None}$ 
    have conflicting  $S \neq \text{None}$  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) full-def by auto
    then have  $S' = S''$  using c
      by (induct rule: rtrancpl-induct)
      (fastforce intro: option.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  $S' = \text{None}$  and
    D-L:  $\forall D \in \# \text{clauses } S'. \text{trail } S' \models_{\text{as}} \text{CNot } D$ 
 $\longrightarrow$  ( $\exists L. L \in \# D \wedge \text{get-level}(\text{trail } S') L = \text{backtrack-lvl } S')$ 
  { assume  $\forall D \in \# \text{clauses } S'. \neg \text{trail } S' \models_{\text{as}} \text{CNot } D$ 

```

```

then have no-clause-is-false S' using confl by simp
then have conflict-is-false-with-level S'' using calculation(3) by presburger
}
moreover {
  assume  $\neg(\forall D \in \# \text{clauses } S'. \neg \text{trail } S' \models_{as} CNot D)$ 
  then obtain T D where
    propagate** S' T and
    conflict T S'' and
    D:  $D \in \# \text{clauses } S'$  and
    trail S''  $\models_{as} CNot D$  and
    conflicting S'' = Some D
  using full1-cdclW-cp-exists-conflict-full1-decompose[OF - - confl]
  other'(3) by (metis (mono-tags, lifting) ball-msetI bex-msetI conflictE state-eq-trail
    trail-update-conflicting)
  obtain M where M: trail S'' = M @ trail S' and nm:  $\forall m \in \text{set } M. \neg \text{is-marked } m$ 
  using rtrancpl-cdclW-cp-dropWhile-trail other'(3) unfolding full-def by meson
  have btS: backtrack-lvl S'' = backtrack-lvl S'
  using other'.hypos(3) unfolding full-def by (metis rtrancpl-cdclW-cp-backtrack-lvl)
  have inv: cdclW-M-level-inv S''
  by (metis (no-types) cdclW-stgy.conflict' cdclW-stgy-consistent-inv full-unfold lev'
    other'.hypos(3))
  then have nd: no-dup (trail S'')
  by (metis (no-types) cdclW-M-level-inv-decomp(2))
  have conflict-is-false-with-level S''
  proof cases
    assume trail S'  $\models_{as} CNot D$ 
    moreover then obtain L where
      L  $\in \# D$  and
      lev-L: get-level (trail S') L = backtrack-lvl S'
      using D-L D by blast
    moreover
      have LS':  $-L \in \text{lits-of } (trail S')$ 
      using  $\langle \text{trail } S' \models_{as} CNot D \rangle \langle L \in \# D \rangle$  in-CNot-implies-uminus(2) by blast
    {
      fix x :: ('v, nat, 'v literal multiset) marked-lit and
      xb :: ('v, nat, 'v literal multiset) marked-lit
      assume a1:  $x \in \text{set } (trail S')$  and
      a2:  $xb \in \text{set } M$  and
      a3:  $(\lambda l. \text{atm-of } (lit-of l)) \text{ ' set } M \cap (\lambda l. \text{atm-of } (lit-of l)) \text{ ' set } (trail S') = \{\}$  and
      a4:  $-L = \text{lit-of } x$  and
      a5:  $\text{atm-of } L = \text{atm-of } (lit-of xb)$ 
      moreover have  $\text{atm-of } (lit-of x) = \text{atm-of } L$ 
      using a4 by (metis (no-types) 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 nd LS' unfolding M by (auto simp add: lits-of-def)
    then have get-level (trail S'') L = get-level (trail S') L
    unfolding M by (simp add: lits-of-def)
    ultimately show ?thesis using btS  $\langle \text{conflicting } S'' = \text{Some } D \rangle$  by auto
  next
    assume  $\neg \text{trail } S' \models_{as} CNot D$ 
    then obtain L where L  $\in \# D$  and LM:  $-L \in \text{lits-of } M$ 
    using  $\langle \text{trail } S'' \models_{as} CNot D \rangle$ 

```

```

    by (auto simp add: CNot-def true-cls-def M true-annots-def true-annot-def
        split: split-if-asm)
  { fix x :: ('v, nat, 'v literal multiset) marked-lit and
    xb :: ('v, nat, 'v literal multiset) marked-lit
    assume a1: xb ∈ set (trail S') and
      a2: x ∈ set M and
      a3: atm-of L = atm-of (lit-of xb) and
      a4: - L = lit-of x and
      a5: (λl. atm-of (lit-of l)) ' set M ∩ (λl. atm-of (lit-of l)) ' set (trail S')
        = {}
    moreover have atm-of (lit-of xb) = atm-of (- L)
      using a3 by simp
    ultimately have False
      by auto }
  then have LS': atm-of L ∉ atm-of ' lits-of (trail S')
    using nd ⟨L ∈ # D⟩ LM unfolding M by (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-level M L = 0
          using nm by auto
        then have get-level (M @ trail S') L = 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'' = Some 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'' = Some 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' ≠ None
  have no-clause-is-false S' using ⟨conflicting S' ≠ None⟩ by auto
  then have conflict-is-false-with-level S'' using calculation(3) by presburger
}

```

```

}
ultimately show ?case by fast
qed

lemma rtrancpl-cdclW-stgy-no-smaller-confl-inv:
  assumes
    cdclW-stgy**  $S\ S'$  and
    n-l: no-smaller-confl  $S$  and
    cls-false: conflict-is-false-with-level  $S$  and
    lev: cdclW-M-level-inv  $S$  and
    no-f: no-clause-is-false  $S$  and
    dist: distinct-cdclW-state  $S$  and
    conflicting: cdclW-conflicting  $S$  and
    decomp: all-decomposition-implies-m (init-clss  $S$ ) (get-all-marked-decomposition (trail  $S$ )) and
    learned: cdclW-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: rtrancpl-induct)
  case base
  then show ?case using n-l cls-false by auto
next
  case (step  $S' S''$ ) note st = this(1) and cdcl = this(2) and IH = this(3)
  have no-smaller-confl  $S'$  and conflict-is-false-with-level  $S'$ 
    using IH by blast+
  moreover have cdclW-M-level-inv  $S'$ 
    using st lev rtrancpl-cdclW-stgy-rtrancpl-cdclW
    by (blast intro: rtrancpl-cdclW-consistent-inv)+
  moreover have no-clause-is-false  $S'$ 
    using st no-f rtrancpl-cdclW-stgy-not-non-negated-init-clss by presburger
  moreover have distinct-cdclW-state  $S'$ 
    using rtancpl-distinct-cdclW-state-inv[of  $S\ S'$ ] lev rtrancpl-cdclW-stgy-rtrancpl-cdclW[OF st]
    dist by auto
  moreover have cdclW-conflicting  $S'$ 
    using rtrancpl-cdclW-all-inv(6)[of  $S\ S'$ ] st alien conflicting decomp dist learned lev
    rtrancpl-cdclW-stgy-rtrancpl-cdclW by blast
  ultimately show ?case
    using cdclW-stgy-no-smaller-confl[OF cdcl] cdclW-stgy-ex-lit-of-max-level[OF cdcl] by fast
qed

```

17.6.7 Final States are Conclusive

```

lemma full-cdclW-stgy-final-state-conclusive-non-false:
  fixes  $S' :: 'st$ 
  assumes full: full cdclW-stgy (init-state  $N$ )  $S'$ 
  and no-d: distinct-mset-mset  $N$ 
  and no-empty:  $\forall D \in \#N. D \neq \{\#\}$ 
  shows (conflicting  $S' = \text{Some } \{\#\} \wedge \text{unsatisfiable } (\text{set-mset } (\text{init-clss } S'))$ )
     $\vee$  (conflicting  $S' = \text{None} \wedge \text{trail } S' \models_{\text{asm}} \text{init-clss } S')$ 
proof -
  let ?S = init-state  $N$ 
  have
    termi:  $\forall S''. \neg \text{cdcl}_W\text{-stgy } S' S''$  and
    step: cdclW-stgy** (init-state  $N$ )  $S'$  using full unfolding full-def by auto
  moreover have
    learned: cdclW-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
conf: $cdcl_W$ -conflicting S' and
decomp: all-decomposition-implies- m ($init_cls$ S') ($get_all_marked_decomposition$ ($trail$ S'))
using *no-d* $trancpl$ - $cdcl_W$ -*stgy*- $trancpl$ - $cdcl_W$ [*of* ? S S'] *step* $rtrancpl$ - $cdcl_W$ -all-inv($1-6$)[*of* ? S S']
unfolding $rtrancpl$ -*unfold* **by** *auto*
moreover
have $\forall D \in \#N. \neg [] \models_{as} CNot\ D$ **using** *no-empty* **by** *auto*
then have *conf*- k : *conflict-is-false-with-level* S'
using $rtrancpl$ - $cdcl_W$ -*stgy*-no-smaller-conf-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* *conf* *conf*- 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* $S' \neq None$ **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 \langle *conflicting* $S' \neq None$ \rangle **by** (*metis* $cdcl_W$ -*cp*-*conflicting-not-empty* *option.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* $S \neq None$
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* $S \neq None$
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* $S \neq None$
shows *False*
using *assms* **apply** (*induct* *rule*: $cdcl_W$ -*stgy.induct*)
using $trancplD$ $cdcl_W$ -*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 $S' \implies$ *conflicting* $S = Some\ \{\#\} \implies False$

```

by (induction rule: cdclW-cp.induct) auto

lemma rtrancpl-cdclW-cp-conflicting-is-false:
  cdclW-cp++ S S'  $\implies$  conflicting S = Some {#}  $\implies$  False
  apply (induction rule: trancpl.induct)
  by (auto dest: cdclW-cp-conflicting-is-false)

lemma cdclW-o-conflicting-is-false:
  cdclW-o S S'  $\implies$  conflicting S = Some {#}  $\implies$  False
  by (induction rule: cdclW-o.induct) auto

lemma cdclW-stgy-conflicting-is-false:
  cdclW-stgy S S'  $\implies$  conflicting S = Some {#}  $\implies$  False
  apply (induction rule: cdclW-stgy.induct)
  unfolding full1-def apply (metis (no-types) cdclW-cp-conflicting-not-empty trancplD)
  unfolding full-def by (metis conflict-with-false-implies-terminated other)

lemma rtrancpl-cdclW-stgy-conflicting-is-false:
  cdclW-stgy* S S'  $\implies$  conflicting S = Some {#}  $\implies$  S' = S
  apply (induction rule: rtrancpl.induct)
  apply simp
  using cdclW-stgy-conflicting-is-false by blast

lemma full-cdclW-init-clss-with-false-normal-form:
  assumes
     $\forall m \in \text{set } M. \neg \text{is-marked } m$  and
    E = Some D and
    state S = (M, N, U, 0, E)
  full cdclW-stgy S S' and
  all-decomposition-implies-m (init-clss S) (get-all-marked-decomposition (trail S))
  cdclW-learned-clause S
  cdclW-M-level-inv S
  no-strange-atm S
  distinct-cdclW-state S
  cdclW-conflicting S
  shows  $\exists M''. \text{state } S' = (M'', N, U, 0, \text{Some } \{ \# \})$ 
  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 rtrancpl-cdclW-stgy-conflicting-is-false unfolding full-def cdclW-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 cdclW-conflicting-def by auto
  then have MpK: M  $\models_{\text{as}}$  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 ≠ {#} by blast
then show ?case
proof cases
  case D
  then show ?thesis
    using full rtracp-cdclW-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 cdclW-cp S by (auto simp: cdclW-cp.simps)
  have res-skip: ∃ T. (resolve S T ∧ no-step skip S ∧ full cdclW-cp T T)
    ∨ (skip S T ∧ no-step resolve S ∧ full cdclW-cp T T)
  proof cases
    assume -lit-of L ∉# 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 cdclW-cp T T
      using sk by (auto simp add: option-full-cdclW-cp)
    then show ?thesis
      using sk res by blast
  next
    assume LD: ¬-lit-of L ∉# D
    then have D: Some D = Some ((D - {#-lit-of L#}) + {#-lit-of L#})
      by (auto simp add: multiset-eq-iff)

    have ∧L. get-level M L = 0
      by (simp add: nm)
    then have get-maximum-level (Propagated K (p - {#K#} + {#K#}) # M) (D - {#-
K#}) = 0
      using LD get-maximum-level-exists-lit-of-max-level
    proof -
      obtain L' where get-level (L#M) L' = get-maximum-level (L#M) D
        using LD get-maximum-level-exists-lit-of-max-level[of D L#M] by fastforce
      then show ?thesis by (metis (mono-tags) K' bex-msetE get-level-skip-all-not-marked
        get-maximum-level-exists-lit nm not-gr0)
    qed
    then obtain T where sk: resolve S T and res: no-step skip S
      using resolve-rule[of S K p - {#K#} M N U 0 (D - {#-K#})
        update-conflicting (Some (remdups-mset (D - {#-K#} + (p - {#K#})))) (tl-trail S)]
        S unfolding K' D E by fastforce
    have full cdclW-cp T T
      using sk by (auto simp add: option-full-cdclW-cp)
    then show ?thesis
      using sk res by blast
  qed
  then have step-s: ∃ T. cdclW-stgy S T
    using (no-step cdclW-cp S) other' by (meson bj resolve skip)
  have get-all-marked-decomposition (L # M) = [([], L#M)]
    using nm unfolding K apply (induction M rule: marked-lit-list-induct, simp)
    by (rename-tac L l xs, case-tac hd (get-all-marked-decomposition xs), auto)+
  then have no-b: no-step backtrack S
    using nm S by auto
  have no-d: no-step decide S
    using S E by auto

```

```

have full-S-S: full cdclW-cp S S
  using S E by (auto simp add: option-full-cdclW-cp)
then have no-f: no-step (full1 cdclW-cp) S
  unfolding full-def full1-def rtrancpl-unfold by (meson trancplD)
obtain T where
  s: cdclW-stgy S T and st: cdclW-stgy** T S'
  using full step-s full unfolding full-def by (metis rtrancpl-unfold trancplD)
have resolve S T ∨ skip S T
  using s no-b no-d res-skip full-S-S unfolding cdclW-stgy.simps cdclW-o.simps full-unfold
  full1-def
  by (auto dest!: trancplD simp: cdclW-bj.simps)
then obtain D' where T: state T = (M, N, U, 0, Some D')
  using S E by auto

have st-c: cdclW** 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' = Some {#} ∧ 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  $\exists T. \text{conflict } ?S \ T$ 
  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 rtranclp-cdclW-cp-backtrack-lvl unfolding full1-def
  by (fastforce dest!: tranclp-into-rtranclp)
have cls-St: init-clss St = N
  using fullSt cdclW-stgy-no-more-init-clss[OF St] by auto
have conflicting St  $\neq$  None
  proof (rule ccontr)
    assume  $\neg ?thesis$ 
    then have  $\exists T. \text{conflict } St \ T$ 
      using empty cls-St[] conflict-rule[of St trail St N learned-clss St backtrack-lvl St
        {#}]
      by (auto simp: clauses-def)
    then show False using fullSt unfolding full1-def by blast
  qed

have 1:  $\forall m \in \text{set } (\text{trail } St). \neg \text{is-marked } m$ 
  using fullSt unfolding full1-def by (auto dest!: tranclp-into-rtranclp
    rtranclp-cdclW-cp-dropWhile-trail)
have 2: full cdclW-stgy St S'
  using  $\langle \text{cdcl}_W\text{-stgy}^{**} \ St \ S' \rangle \langle \text{no-step } \text{cdcl}_W\text{-stgy } S' \rangle \text{bt}$  unfolding full-def by auto
have 3: all-decomposition-implies-m
  (init-clss St)
  (get-all-marked-decomposition
    (trail St))
  using rtranclp-cdclW-all-inv(1)[OF st] no-d bt by simp
have 4: cdclW-learned-clause St
  using rtranclp-cdclW-all-inv(2)[OF st] no-d bt bt by simp
have 5: cdclW-M-level-inv St
  using rtranclp-cdclW-all-inv(3)[OF st] no-d bt by simp
have 6: no-strange-atm St
  using rtranclp-cdclW-all-inv(4)[OF st] no-d bt by simp
have 7: distinct-cdclW-state St
  using rtranclp-cdclW-all-inv(5)[OF st] no-d bt by simp
have 8: cdclW-conflicting St
  using rtranclp-cdclW-all-inv(6)[OF st] no-d bt by simp
have init-clss S' = init-clss St and conflicting S' = Some {#}
  using  $\langle \text{conflicting } St \neq \text{None} \rangle \text{full-cdcl}_W\text{-init-clss-with-false-normal-form}[OF \ 1, \text{of } - \ St]$ 
  2 3 4 5 6 7 8 St apply (metis  $\langle \text{cdcl}_W\text{-stgy}^{**} \ St \ S' \rangle \text{rtranclp-cdcl}_W\text{-stgy-no-more-init-clss}$ )
  using  $\langle \text{conflicting } St \neq \text{None} \rangle \text{full-cdcl}_W\text{-init-clss-with-false-normal-form}[OF \ 1, \text{of } - \ St \ - \$ 
    S'] 2 3 4 5 6 7 8 by (metis bt option.exhaust prod.inject)

moreover have init-clss S' = N
  using  $\langle \text{cdcl}_W\text{-stgy}^{**} \ (\text{init-state } N) \ S' \rangle \text{rtranclp-cdcl}_W\text{-stgy-no-more-init-clss}$  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 cdclW-stgy (init-state N) S' and no-d: distinct-mset-mset N
shows (conflicting S' = Some {#} ∧ unsatisfiable (set-mset (init-clss S')))
  ∨ (conflicting S' = None ∧ trail S' ⊨asm init-clss S')
using assms full-cdclW-stgy-final-state-conclusive-is-one-false
full-cdclW-stgy-final-state-conclusive-non-false by blast

lemma full-cdclW-stgy-final-state-conclusive-from-init-state:
fixes S' :: 'st
assumes full: full cdclW-stgy (init-state N) S'
and no-d: distinct-mset-mset N
shows (conflicting S' = Some {#} ∧ unsatisfiable (set-mset N))
  ∨ (conflicting S' = None ∧ trail S' ⊨asm N ∧ satisfiable (set-mset N))
proof -
have N: init-clss S' = N
  using full unfolding full-def by (auto dest: rtrancp-cdclW-stgy-no-more-init-clss)
consider
  (confl) conflicting S' = Some {#} and unsatisfiable (set-mset (init-clss S'))
  | (sat) conflicting S' = None and trail S' ⊨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') ⊨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
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 *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 ∧ cdclW-M-level-inv S
  ∧ (∀ s ∈ # learned-clss S. ¬tautology s)
  ∧ distinct-cdclW-state S ∧ cdclW-conflicting S
  ∧ all-decomposition-implies-m (init-clss S) (get-all-marked-decomposition (trail S))

```

\wedge *cdcl_W-learned-clause S*)

lemma *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'*

unfolding *cdcl_W-all-struct-inv-def*

proof (*intro HOL.conjI*)

show *no-strange-atm S'*

using *cdcl_W-all-inv[OF assms(1)] assms(2) unfolding cdcl_W-all-struct-inv-def by auto*

show *cdcl_W-M-level-inv S'*

using *cdcl_W-all-inv[OF assms(1)] assms(2) unfolding cdcl_W-all-struct-inv-def by fast*

show *distinct-cdcl_W-state S'*

using *cdcl_W-all-inv[OF assms(1)] assms(2) unfolding cdcl_W-all-struct-inv-def by fast*

show *cdcl_W-conflicting S'*

using *cdcl_W-all-inv[OF assms(1)] assms(2) unfolding cdcl_W-all-struct-inv-def by fast*

show *all-decomposition-implies-m (init-clss S') (get-all-marked-decomposition (trail S'))*

using *cdcl_W-all-inv[OF assms(1)] assms(2) unfolding cdcl_W-all-struct-inv-def by fast*

show *cdcl_W-learned-clause S'*

using *cdcl_W-all-inv[OF assms(1)] assms(2) unfolding cdcl_W-all-struct-inv-def by fast*

show $\forall s \in \# \text{learned-clss } S'. \neg \text{tautology } s$

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 = Some 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)*

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*: $D \in \# \text{ learned-clss } T$ **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 $\exists S'. \text{ backtrack } S \ S' \wedge \text{ cdcl}_W\text{-stgy}^{**} S' \ T \wedge \text{ conflicting } S = \text{Some } D$
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*
trancplp-into-rtranclp)
next
case (*other'* $S' \ S''$)
then have $D \in \# \text{ learned-clss } S'$
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-rtranclp*
rtranclp.rtrancl-refl)
qed

lemma *rtranclp-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 $\exists S' \ S''. \text{ cdcl}_W\text{-stgy}^{**} S \ S' \wedge \text{ backtrack } S' \ S'' \wedge \text{ conflicting } S' = \text{Some } D \wedge$
 $\text{ cdcl}_W\text{-stgy}^{**} S'' \ T$
using *cdcl_W learned new*
proof (*induction rule*: *rtranclp-induct*)
case *base*
then show ?*case* **by** *blast*
next
case (*step* $T \ U$) **note** $st = \text{this}(1)$ **and** $o = \text{this}(2)$ **and** $IH = \text{this}(3)$ **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* $S' = \text{Some } D$ **and**
 st'' : *cdcl_W-stgy*^{**} $S'' \ T$
using $IH \ D \cdot S$ **by** *metis*
then show ?*thesis* **using** o **by** (*meson rtranclp.simps*)
next
case *False*
have *cdcl_W-M-level-inv* T
using *lev rtranclp-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* $T = \text{Some } D$

```

    using cdclW-cp-new-clause-learned-has-backtrack-step[OF D-U False o]
    by metis
  then have cdclW-stgy** S T and
    backtrack T S' and
    conflicting T = Some D and
    cdclW-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 $T = \text{this}(7)$ and $\text{lev} = \text{this}(8)$
 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 $\text{st} = \text{this}(1)$ and $\text{no-dup} = \text{this}(2)$ and $S' = \text{this}(3)$ and $S = \text{this}(4)$

```

have cdclW-M-level-inv S'
  using full1-cdclW-cp-consistent-inv no-dup st by blast
then have Marked L i ∈ set (trail S') and Marked L i ∉ set (trail S)
  using no-dup unfolding S S' cdclW-M-level-inv-def by (auto simp add: rev-image-eqI)
then have False
  using st rtrancp-cdclW-cp-no-more-Marked-lit[of S S']
  unfolding full1-def rtrancp-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 cdclW-M-level-inv U
  by (metis (full-types) lev cdclW.simps cdclW-consistent-inv full-def o
    other'.hyps(3) rtrancp-cdclW-cp-consistent-inv)
then have Marked L i ∈ set (trail U) and Marked L i ∉ set (trail S)
  using no-dup unfolding S S' cdclW-M-level-inv-def by (auto simp add: rev-image-eqI)
then have Marked L i ∈ set (trail T)
  using st rtrancp-cdclW-cp-no-more-Marked-lit unfolding full-def by blast
then show ?case
  using cdclW-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 cdclW-o S' T and cdclW-M-level-inv S'
  trail T = drop (length M0) M' @ Marked L i # H @ M and
  ¬ (∃ M'. trail S' = M' @ Marked L i # H @ M)
shows decide S' T
  using assms
proof (induction rule:cdclW-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: cdclW-M-level-inv-def)
next
case decide
show ?case using decide-rule[of S'] decide(1-4) by auto
qed auto

```

lemma *rtrancp-cdcl_W-new-marked-at-beginning-is-decide:*

```

assumes cdclW-stgy** R U and
  trail U = M' @ Marked L i # H @ M and
  trail R = M and
  cdclW-M-level-inv R
shows
  ∃ S T T'. cdclW-stgy** R S ∧ decide S T ∧ cdclW-stgy** T U ∧ cdclW-stgy** S U ∧
  no-step cdclW-cp S ∧ trail T = Marked L i # H @ M ∧ trail S = H @ M ∧ cdclW-stgy S T' ∧
  cdclW-stgy** T' U
  using assms
proof (induct arbitrary: M H M' i rule: rtrancp-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 M_0 where $\text{trail } W = M_0 @ \text{trail } T$ and $n\text{marked}: \forall l \in \text{set } M_0. \neg \text{is-marked } l$

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) $M' = M_0 @ \text{takeWhile } (\text{Not } o \text{ is-marked}) (\text{trail } T)$

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 $\text{length } M_0 \leq \text{length } M'$

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 M_0 where $\text{trail } U = M_0 @ \text{trail } T'$ and $n\text{marked}: \forall l \in \text{set } M_0. \neg \text{is-marked } l$

using rtrancpl-cdcl_W-cp-dropWhile-trail cp unfolding full-def by meson

then have $MV: M' @ \text{Marked } L \ i \ \# \ H @ M = M_0 @ \text{trail } T'$ unfolding U 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) $M' = M_0 @ \text{takeWhile } (\text{Not } o \text{ is-marked}) (\text{trail } T')$

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 $\text{length } M_0 \leq \text{length } M'$

unfolding length-append by (metis (no-types, lifting) Nat.le-trans le-add1 length-takeWhile-le)

then have $tr-T': \text{trail } T' = \text{drop } (\text{length } M_0) M' @ \text{Marked } L \ i \ \# \ H @ M$ using V by auto

then have $LT': \text{Marked } L \ i \in \text{set } (\text{trail } T')$ by auto

moreover

have cdcl_W-M-level-inv T

using lev rtrancpl-cdcl_W-stgy-consistent-inv step.hyps(1) by blast

then have decide T T' using o nd tr-T' cdcl_W-o-is-decide by metis

ultimately have decide T T' using cdcl_W-o-no-more-Marked-lit[OF o] by blast

then have 1: cdcl_W-stgy** R T and 2: decide T T' and 3: cdcl_W-stgy** T' U

using st other'.prems(4)

by (metis cdcl_W-stgy.conflict' cp full-unfold r-into-rtrancpl rtrancpl.rtrancpl-refl)+

have [simp]: $\text{drop } (\text{length } M_0) M' = []$

using <decide T T'> <Marked L i ∈ set (trail T')> nd tr-T'

by (auto simp add: Cons-eq-append-conv)

have T': $\text{drop } (\text{length } M_0) M' @ \text{Marked } L \ i \ \# \ H @ M = \text{Marked } L \ i \ \# \ \text{trail } T$

using <decide T T'> <Marked L i ∈ set (trail T')> nd tr-T'

by auto

have $\text{trail } T' = \text{Marked } L \ i \ \# \ \text{trail } T$

using <decide T T'> <Marked L i ∈ set (trail T')> tr-T'

by auto

then have 5: $\text{trail } T' = \text{Marked } L \ i \ \# \ H @ M$

using append.simps(1) list.sel(3) local.other'(5) tl-append2 by (simp add: tr-T')

have 6: $\text{trail } T = H @ M$

```

    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: trail S' = H @ M and
  8: cdclW-stgy** S' T and
  9: cdclW-stgy S' S''' and
  10: cdclW-stgy** S''' T
    by blast
  have cdclW-stgy** S'' U using s ⟨cdclW-stgy** S'' T⟩ by auto
  moreover have cdclW-stgy** S' U using 8 s by auto
  moreover have cdclW-stgy** S''' U using 10 s by auto
  ultimately show ?thesis apply - apply (rule exI[of - S'], rule exI[of - S''])
    using 1 2 4 6 7 8 9 by blast
qed
qed

lemma rtrancp-cdclW-new-marked-at-beginning-is-decide':
  assumes cdclW-stgy** R U and
  trail U = M' @ Marked L i # H @ M and
  trail R = M and
  cdclW-M-level-inv R
  shows ∃ y y'. cdclW-stgy** R y ∧ cdclW-stgy y y' ∧ ¬ (∃ c. trail y = c @ Marked L i # H @ M)
    ∧ (λa b. cdclW-stgy a b ∧ (∃ c. trail a = c @ Marked L i # H @ M))** y' U
proof -
  fix T'
  obtain S' T T' where
    st: cdclW-stgy** R S' and
    decide S' T and
    TU: cdclW-stgy** T U and
    no-step cdclW-cp S' and
    trT: trail T = Marked L i # H @ M and
    trS': trail S' = H @ M and
    S'U: cdclW-stgy** S' U and
    S'T': cdclW-stgy S' T' and
    T'U: cdclW-stgy** T' U
    using rtrancp-cdclW-new-marked-at-beginning-is-decide[OF assms] by blast
  have n: ¬ (∃ c. trail S' = c @ Marked L i # H @ M) using trS' by auto
  show ?thesis
    using rtrancp-trans[OF st] rtrancp-exists-last-with-prop[of cdclW-stgy S' T' -
      λa -. ¬(∃ c. trail a = c @ Marked L i # H @ M), 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 $\text{arg-cong}[OF \ A, \text{ of } \text{drop } (\text{length } M)]$ 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 $\text{marked-lit.disc}(1)$ not-gr0 nth-append nth-append-length nth-mem zero-less-diff)

finally show ?thesis by fast

qed

lemma $\text{cdcl}_W\text{-stgy-trail-has-new-marked-is-decide-step}$:

assumes $\text{cdcl}_W\text{-stgy } S \ T$

$\neg (\exists c. \text{trail } S = c @ \text{Marked } L \ i \ \# \ H @ M)$ and

$(\lambda a \ b. \text{cdcl}_W\text{-stgy } a \ b \wedge (\exists c. \text{trail } a = c @ \text{Marked } L \ i \ \# \ H @ M))^{**} \ T \ U$ and

$\exists M'. \text{trail } U = M' @ \text{Marked } L \ i \ \# \ H @ M$ and

$\text{lev}: \text{cdcl}_W\text{-M-level-inv } S$

shows $\exists S'. \text{decide } S \ S' \wedge \text{full } \text{cdcl}_W\text{-cp } S' \ T \wedge \text{no-step } \text{cdcl}_W\text{-cp } S$

using $\text{assms}(3,1,2,4,5)$

proof induction

case (step $T \ U$)

then show ?case by fastforce

next

case base

then show ?case

proof (induction rule: $\text{cdcl}_W\text{-stgy.induct}$)

case (conflict' T) note $cp = \text{this}(1)$ and $nd = \text{this}(2)$ and $M' = \text{this}(3)$ and $\text{no-dup} = \text{this}(3)$

then obtain M' where $M': \text{trail } T = M' @ \text{Marked } L \ i \ \# \ H @ M$ by metis

obtain M'' where $M'': \text{trail } T = M'' @ \text{trail } S$ and $nm: \forall m \in \text{set } M''. \neg \text{is-marked } m$

using cp unfolding full1-def

by (metis $\text{rtranclp-cdcl}_W\text{-cp-dropWhile-trail'}$ $\text{tranclp-into-rtranclp}$)

have False

using $\text{beginning-not-marked-invert}[of \ M'' \ \text{trail } S \ M' \ L \ i \ H @ M] \ M' \ nm \ nd$ unfolding M''

by fast

then show ?case by fast

next

case (other' $T \ U'$) note $o = \text{this}(1)$ and $ns = \text{this}(2)$ and $cp = \text{this}(3)$ and $nd = \text{this}(4)$

and $\text{tr}U' = \text{this}(5)$

have $\text{cdcl}_W\text{-cp}^{**} \ T \ U'$ using cp unfolding full-def by blast

from $\text{rtranclp-cdcl}_W\text{-cp-dropWhile-trail}[OF \ \text{this}]$

have $\exists M'. \text{trail } T = M' @ \text{Marked } L \ i \ \# \ H @ M$

using $\text{tr}U'$ $\text{beginning-not-marked-invert}[of \ - \ \text{trail } T - L \ i \ H @ M]$ by metis

then obtain M' where $M': \text{trail } T = M' @ \text{Marked } L \ i \ \# \ H @ M$

by auto

with $o \ \text{lev} \ nd \ cp \ ns$

show ?case

proof (induction rule: $\text{cdcl}_W\text{-o-induct-lev2}$)

case (decide L) note $\text{dec} = \text{this}(1)$ and $cp = \text{this}(5)$ and $ns = \text{this}(4)$

then have $\text{decide } S \ (\text{cons-trail } (\text{Marked } L \ (\text{backtrack-lvl } S + 1)) \ (\text{incr-lvl } S))$

using decide.hyps $\text{decide.intros}[of \ S]$ 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 *rtranclp-cdcl_W-stgy-with-trail-end-has-trail-end:*

```

  assumes (λa 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
  shows ∃ M'. trail T = M' @ Marked L i # H @ M
  using assms by (induction rule: rtranclp-induct) auto

```

lemma *cdcl_W-o-cannot-learn:*

```

  assumes
    cdclW-o y z and
    lev: cdclW-M-level-inv y and
    trM: trail y = c @ Marked Kh i # H and
    DL: 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
    learned: ∀ T. conflicting y = Some T ⟶ trail y ⊨as CNot T and
    z: trail z = c' @ Marked Kh i # H
  shows D + {#L#} ∉ # learned-clss z
  using assms(1-2) trM DL DH LH learned z
proof (induction rule: cdclW-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 = this(7)
  obtain M3 where M3: trail y = M3 @ M2 @ Marked K (Suc j) # M1
    using decomp get-all-marked-decomposition-exists-prepend by metis
  have M: trail y = c @ Marked Kh i # H using trM by simp
  have H: get-all-levels-of-marked (trail y) = rev [1..1 + backtrack-lvl y]
    using lev unfolding cdclW-M-level-inv-def by auto
  have c' @ Marked Kh i # H = Propagated L' (D' + {#L'##}) # trail (reduce-trail-to M1 y)
    using backtrack.premis(6) decomp undef T lev by (force simp: cdclW-M-level-inv-def)
  then obtain d where d: M1 = d @ 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 ∈ set (get-all-levels-of-marked (M3 @ M2 @ Marked K (Suc j) # d @ Marked Kh i # H))
    by auto
  then have i > 0 unfolding H[unfolded M3 d] by auto
  show ?case
  proof
    assume D + {#L#} ∈ # learned-clss T

```

```

then have DLD':  $D + \{\#L\# \} = D' + \{\#L'\#\}$ 
  using DL T neq0-conv undef decomp lev by (fastforce simp: cdclW-M-level-inv-def)
have L-cKh: atm-of L  $\in$  atm-of 'lits-of (c @ [Marked Kh i])
  using LH learned M DLD'[symmetric] confl by (fastforce simp add: image-iff)
have get-all-levels-of-marked (M3 @ M2 @ Marked K (j + 1) # M1)
  = rev [1.. $1 + \text{backtrack-lvl } y$ ]
  using lev unfolding cdclW-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 (trail y)  $L' \leq \text{get-maximum-level (trail y) } D$ 
    using get-maximum-level-ge-get-level by blast
  moreover {
    have get-maximum-level (trail y)  $D = \text{get-maximum-level } H D$ 
      using DH unfolding M by (simp add: get-maximum-level-skip-beginning)
    moreover
      have get-all-levels-of-marked (trail y) = rev [1.. $1 + \text{backtrack-lvl } y$ ]
        using lev unfolding cdclW-M-level-inv-def by auto
      then have get-all-levels-of-marked  $H = \text{rev } [1..< i]$ 
        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 (trail y)  $D < i$ 
        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 (trail y)  $D' \geq \text{get-level (trail y) } L$ 
      using get-maximum-level-ge-get-level by blast
    moreover {
      have get-all-levels-of-marked (c @ [Marked Kh i]) = rev [ $i..< \text{backtrack-lvl } y + 1$ ]
        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 (trail y)  $L = \text{get-level (c @ [Marked Kh i]) } L$ 
        using L-cKh LH unfolding M by simp
      have get-level (c @ [Marked Kh i])  $L \geq i$ 
        using L-cKh
           $\langle \text{get-all-levels-of-marked (c @ [Marked Kh i])} = \text{rev } [i..< \text{backtrack-lvl } y + 1] \rangle$ 
        backtrack.hyps(2) calculation(1,2) by auto
      then have get-level (trail y)  $L \geq i$ 
        using M  $\langle \text{get-level (trail y) } L = \text{get-level (c @ [Marked Kh i]) } L \rangle$  by auto }
    moreover have get-maximum-level (trail y)  $D' < \text{get-level (trail y) } L$ 
      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''  $\in$  #D' and
    L''D': get-level (trail y) L'' = get-maximum-level (trail y) D'
    using get-maximum-level-exists-lit-of-max-level[OF D, of trail y] by auto
  have L''M: atm-of L''  $\in$  atm-of ' lits-of (trail y)
    using get-rev-level-ge-0-atm-of-in[of 0 rev (trail y) L'']  $\langle j > 0 \rangle$  levD L''D' by auto
  then have L''  $\in$  lits-of (Marked Kh i # d)
  proof -
    {
      assume L''H: atm-of L''  $\in$  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 (trail y) L'' = get-level H L''
        using L''H unfolding M by simp
      ultimately have False
        using levD  $\langle j > 0 \rangle$  get-rev-level-in-levels-of-marked[of rev H 0 L'']  $\langle i \leq j \rangle$ 
        unfolding L''D'[symmetric] nd by auto
    }
    then show ?thesis
      using DD' DH  $\langle L'' \in \# D' \rangle$  atm-of-lit-in-atms-of contra-subsetD by metis
  qed
  then have False
    using DH  $\langle L'' \in \# D' \rangle$  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 *cdcl_W-stgy y z* **and**
cdcl_W-M-level-inv y **and**
trail y = c @ Marked Kh i # H **and**
D + {#L#} \notin learned-clss y **and**
DH: atms-of D \subseteq atm-of ' lits-of H **and**

$LH: atm\text{-}of\ L \notin atm\text{-}of\ 'lits\text{-}of\ H$ and
 $\forall T. conflicting\ y = Some\ T \longrightarrow trail\ y \models_{as}\ CNot\ T$ and
 $trail\ z = c' @ Marked\ Kh\ i \# H$
shows $D + \{\#L\# \} \notin \# learned\text{-}clss\ z$
using *assms*
proof *induction*
case *conflict'*
then show *?case*
unfolding *full1-def* **using** *trancpl-cdcl_W-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]*
 $rtrancpl\text{-}cdcl_W\text{-}cp\text{-}dropWhile\text{-}trail[of\ T\ U]$ **unfolding** *trU full-def* **by** *fastforce*
show *?case*
using *cdcl_W-o-cannot-learn[OF o lev trY notin DH LH confl c']*
 $rtrancpl\text{-}cdcl_W\text{-}cp\text{-}learned\text{-}clause\text{-}inv\ cp$ **unfolding** *full-def* **by** *auto*
qed

lemma *rtrancpl-cdcl_W-stgy-with-trail-end-has-not-been-learned*:
assumes $(\lambda a\ b. cdcl_W\text{-}stgy\ a\ b \wedge (\exists c. trail\ a = c @ Marked\ K\ i \# H @ []))^{**}\ S\ z$ and
 $cdcl_W\text{-}all\text{-}struct\text{-}inv\ S$ and
 $trail\ S = c @ Marked\ K\ i \# H$ and
 $D + \{\#L\# \} \notin \# learned\text{-}clss\ S$ and
 $DH: atms\text{-}of\ D \subseteq atm\text{-}of\ 'lits\text{-}of\ H$ and
 $LH: atm\text{-}of\ L \notin atm\text{-}of\ 'lits\text{-}of\ H$ and
 $\exists c'. trail\ z = c' @ Marked\ K\ i \# H$
shows $D + \{\#L\# \} \notin \# learned\text{-}clss\ z$
using *assms(1-4,7)*
proof (*induction rule: rtrancpl-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 $DL\text{-}S = this(6)$ 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-rtrancpl*)
then have $cdcl_W\text{-}stgy^{**}\ S\ T$
using st **by** *blast*
then show *?thesis*
using $rtrancpl\text{-}cdcl_W\text{-}stgy\text{-}rtrancpl\text{-}cdcl_W$ **by** *blast*
qed
then have $lev': cdcl_W\text{-}all\text{-}struct\text{-}inv\ T$
using $rtrancpl\text{-}cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}inv[of\ S\ T]$ lev **by** *auto*
then have $confl': \forall Ta. conflicting\ T = Some\ Ta \longrightarrow trail\ T \models_{as}\ CNot\ Ta$
unfolding $cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def\ cdcl_W\text{-}conflicting\text{-}def$ **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** $cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def$ **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 $\exists S'. \text{backtrack } S S' \wedge \text{conflicting } S = \text{Some } E \wedge \text{full } \text{cdcl}_W\text{-cp } S' T$

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* = *Some 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* = *Some E* **and**

already-learned: *E* \in *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* \sim *cons-trail* (*Propagated* *L* ((*D* + {#*L*#})))

(*reduce-trail-to* *M1* (*add-learned-cls* (*D* + {#*L*#})))

(*update-backtrack-lvl* (*get-maximum-level* (*trail* *S*) *D*) (*update-conflicting* *None* *S*)))

and

decomp: (*Marked* *K* (*Suc* (*get-maximum-level* (*trail* *S*) *D*)) # *M1*, *M2-loc*) \in

set (*get-all-marked-decomposition* (*trail* *S*)) **and**

k: *get-level* (*trail* *S*) *L* = *backtrack-lvl* *S* **and**

level: *get-level* (*trail* *S*) *L* = *get-maximum-level* (*trail* *S*) (*D*+{#*L*#}) **and**

confl-S: *conflicting* *S* = *Some* (*D* + {#*L*#}) **and**

i: *i* = *get-maximum-level* (*trail* *S*) *D* **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 $\text{trail } S \models_{as} CNot (D + \{\#L\# \})$ **unfolding** $\text{cdcl}_W\text{-conflicting-def}$ $\text{confl-}S$ **by** *auto*
then have $MD: \text{trail } S \models_{as} CNot D$ **by** *auto*

have $\text{lev}' : \text{cdcl}_W\text{-}M\text{-level-inv } S$ **using** $\text{inv}S$ **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ **by** *blast*

have $\text{get-lvls-}M: \text{get-all-levels-of-marked } (\text{trail } S) = \text{rev } [1..<\text{Suc } (\text{backtrack-lvl } S)]$
using lev' **unfolding** $\text{cdcl}_W\text{-}M\text{-level-inv-def}$ **by** *auto*

have $\text{lev} : \text{cdcl}_W\text{-}M\text{-level-inv } R$ **using** $\text{inv}R$ **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ **by** *blast*
then have $\text{vars-of-}D: \text{atms-of } D \subseteq \text{atm-of ' lits-of } M1$
using $\text{backtrack-atms-of-}D\text{-in-}M1[OF \text{lev}' \text{undef - decomp - - } T] \text{ confl-}S \text{ conf } T \text{ decomp } k \text{ level } \text{lev}' i \text{undef}$ **unfolding** $\text{cdcl}_W\text{-conflicting-def}$ **by** $(\text{auto simp: cdcl}_W\text{-}M\text{-level-inv-def})$
have $\text{no-dup } (\text{trail } S)$ **using** lev' **by** $(\text{auto simp: cdcl}_W\text{-}M\text{-level-inv-decomp})$
have $\text{vars-in-}M1:$
 $\forall x \in \text{atms-of } D. x \notin \text{atm-of ' lits-of } (M2 @ [\text{Marked } K (\text{get-maximum-level } (\text{trail } S) D + 1)])$
apply $(\text{rule vars-of-}D \text{ distinct-atms-of-incl-not-in-other}[of$
 $M2 @ \text{Marked } K (\text{get-maximum-level } (\text{trail } S) D + 1) \# [] M1 D])$
using $\langle \text{no-dup } (\text{trail } S) \rangle M \text{ vars-of-}D$ **by** *simp-all*
have $M1\text{-}D: M1 \models_{as} CNot D$
using $\text{vars-in-}M1 \text{ true-annots-remove-if-notin-vars}[of M2 @ \text{Marked } K (i + 1) \# [] M1 CNot D]$
 $\langle \text{trail } S \models_{as} CNot D \rangle M$ **by** *simp*

have $\text{get-lvls-}M: \text{get-all-levels-of-marked } (\text{trail } S) = \text{rev } [1..<\text{Suc } (\text{backtrack-lvl } S)]$
using lev' **unfolding** $\text{cdcl}_W\text{-}M\text{-level-inv-def}$ **by** *auto*
then have $\text{backtrack-lvl } S > 0$ **unfolding** M **by** $(\text{auto split: split-if-asm simp add: upt.simps}(2))$

obtain $M1' K' Ls$ **where**
 $M': \text{trail } S = Ls @ \text{Marked } K' (\text{backtrack-lvl } S) \# M1'$ **and**
 $Ls: \forall l \in \text{set } Ls. \neg \text{is-marked } l$ **and**
 $\text{set } M1 \subseteq \text{set } M1'$
proof –
let $?Ls = \text{takeWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S)$
have $MLs: \text{trail } S = ?Ls @ \text{dropWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S)$
by *auto*
have $\text{dropWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S) \neq []$ **unfolding** M **by** *auto*
moreover
from $\text{hd-dropWhile}[OF \text{this}]$ **have** $\text{is-marked}(\text{hd } (\text{dropWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S)))$
by *simp*
ultimately
obtain $K' K'k$ **where**
 $K'k: \text{dropWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S)$
 $= \text{Marked } K' K'k \# \text{tl } (\text{dropWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S))$
by $(\text{cases } \text{dropWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S);$
 $\text{cases } \text{hd } (\text{dropWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S)))$
simp-all
moreover have $\forall l \in \text{set } ?Ls. \neg \text{is-marked } l$ **using** set-takeWhileD **by** *force*
moreover
have $\text{get-all-levels-of-marked } (\text{trail } S)$
 $= K'k \# \text{get-all-levels-of-marked}(\text{tl } (\text{dropWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S)))$
apply $(\text{subst } MLs, \text{subst } K'k)$
using $\text{calculation}(2)$ **by** $(\text{auto simp add: get-all-levels-of-marked-no-marked})$
then have $K'k = \text{backtrack-lvl } S$
using $\text{calculation}(2)$ **by** $(\text{auto split: split-if-asm simp add: get-lvls-}M \text{ upt.simps}(2))$
moreover have $\text{set } M1 \subseteq \text{set } (\text{tl } (\text{dropWhile } (\text{Not } o \text{ is-marked}) (\text{trail } S)))$
unfolding M **by** $(\text{induction } M2) \text{ auto}$

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 $\langle \text{set } M1 \subseteq \text{set } M1' \rangle$ 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.. $\text{backtrack-lvl } S$]
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 (trail S) L = get-level M1' L
unfolding M' by auto
then show False using get-level-in-levels-of-marked[of M1' L] $\langle \text{backtrack-lvl } S > 0 \rangle$
unfolding k lvls-M1' by auto
qed

obtain Y Z where
RY: cdcl_W-stgy** R Y and
YZ: cdcl_W-stgy Y Z and
nt: $\neg (\exists c. \text{trail } Y = c @ \text{Marked } K' (\text{backtrack-lvl } S) \# M1' @ [])$ and
Z: $(\lambda a b. \text{cdcl}_W\text{-stgy } a b \wedge (\exists c. \text{trail } a = c @ \text{Marked } K' (\text{backtrack-lvl } S) \# M1' @ []))^{**}$
Z S
using rtranclp-cdcl_W-new-marked-at-beginning-is-decide'[OF st' - - lev, of Ls K'
backtrack-lvl S M1' []]
unfolding R M' by auto
have [simp]: cdcl_W-M-level-inv Y
using RY lev rtranclp-cdcl_W-stgy-consistent-inv by blast
obtain M' where trZ: trail Z = M' @ Marked K' (backtrack-lvl S) # M1'
using rtranclp-cdcl_W-stgy-with-trail-end-has-trail-end[OF Z] M' by auto
have no-dup (trail Y)
using RY lev rtranclp-cdcl_W-stgy-consistent-inv unfolding cdcl_W-M-level-inv-def by blast
then obtain Y' where
dec: decide Y Y' and
Y'Z: full cdcl_W-cp Y' Z and
no-step cdcl_W-cp Y
using cdcl_W-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 rtranclp-cdcl_W-stgy-with-trail-end-has-trail-end[OF Z] M' by auto
obtain M'' where M'': trail Z = M'' @ trail Y' and $\forall m \in \text{set } M''. \neg \text{is-marked } m$
using Y'Z rtranclp-cdcl_W-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) $\langle \forall m \in \text{set } M''. \neg \text{is-marked } m \rangle$ beginning-not-marked-invert)
then show ?thesis using dec nt by (induction M''') auto
qed

have Y-CT: conflicting Y = None using $\langle \text{decide } Y Y' \rangle$ by auto
have cdcl_W** R Y by (simp add: RY rtranclp-cdcl_W-stgy-rtranclp-cdcl_W)
then have init-clss Y = init-clss R using rtranclp-cdcl_W-init-clss[of R Y] M-lev by auto


```

{ assume DL:  $D + \{\#L\} \in \# \text{ clauses } Y$ 
  have atm-of  $L \notin \text{atm-of } \text{'lits-of } M1$ 
    apply (rule backtrack-lit-skipped[of S])
    using decomp  $i \ k \ \text{lev'}$  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  $\exists Y'. \text{propagate } Y \ Y'$ 
    using propagate-rule[of Y] DL  $M1' \text{-} D \ L\text{-trY } Y\text{-CT } \text{trY } DL$  by (metis state-eq-ref)
  then have False using (no-step cdclW-cp Y) propagate' by blast
}
moreover {
  assume DL:  $D + \{\#L\} \notin \# \text{ clauses } Y$ 
  have lY-lZ: learned-clss  $Y = \text{learned-clss } Z$ 
    using dec  $Y'Z$  rtranclp-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-rtranclp rtranclp-cdclW-all-struct-inv-inv
        rtranclp-cdclW-stgy-rtranclp-cdclW)
  have  $D + \{\#L\} \notin \# \text{ learned-clss } S$ 
    apply (rule rtranclp-cdclW-stgy-with-trail-end-has-not-been-learned[OF  $Z \ \text{invZ } \text{trZ}$ ])
    using DL lY-lZ unfolding clauses-def apply simp
    apply (metis (no-types, lifting) (set  $M1 \subseteq \text{set } M1'$ ) 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  $Y = \text{init-clss } R$ ) clauses-def confl-S
        rtranclp-cdclW-stgy-no-more-init-clss)
}
ultimately show False by blast
qed

```

lemma rtranclp-cdcl_W-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: tranclp-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: rtrancpl-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 rtrancpl-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 = Some 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
    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 rtrancpl-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 =
    [(?::nat) ^ (card (atms-of-msu (init-clss S))) - card (set-mset (learned-clss S)),
     if conflicting S = None then 1 else 0,
     if conflicting S = None 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

```

```

context cdclW
begin

```

```

lemma learned-clss-less-upper-bound:
  fixes S :: 'st
  assumes
    distinct-cdclW-state S and

```

$\forall s \in \# \text{ learned-clss } S. \neg \text{tautology } s$
shows $\text{card}(\text{set-mset}(\text{learned-clss } S)) \leq 3 \wedge \text{card}(\text{atms-of-msu}(\text{learned-clss } S))$
proof –
have $\text{set-mset}(\text{learned-clss } S) \subseteq \text{simple-clss}(\text{atms-of-msu}(\text{learned-clss } S))$
apply *(rule simplified-in-simple-clss)*
using *assms unfolding distinct-cdcl_W-state-def* **by** *auto*
then have $\text{card}(\text{set-mset}(\text{learned-clss } S))$
 $\leq \text{card}(\text{simple-clss}(\text{atms-of-msu}(\text{learned-clss } S)))$
by *(simp add: simple-clss-finite card-mono)*
then show *?thesis*
by *(meson atms-of-ms-finite simple-clss-card finite-set-mset order-trans)*
qed

lemma *lexn3[intro!, simp]:*
 $a < a' \vee (a = a' \wedge b < b') \vee (a = a' \wedge b = b' \wedge c < c')$
 $\implies ([a::\text{nat}, b, c], [a', b', c']) \in \text{lexn } \{(x, y). x < y\} \text{ } 3$
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
 $\text{cdcl}_W \text{ } S \text{ } S'$ **and**
 no-restart:
 $\neg(\text{learned-clss } S \subseteq \# \text{ learned-clss } S' \wedge [] = \text{trail } S' \wedge \text{conflicting } S' = \text{None})$
and
 $\text{learned-clss } S \subseteq \# \text{ learned-clss } S'$ **and**
 $\text{no-relearn: } \bigwedge S'. \text{backtrack } S \text{ } S' \implies \forall T. \text{conflicting } S = \text{Some } T \longrightarrow T \notin \# \text{ learned-clss } S$
and
 $\text{alien: no-strange-atm } S$ **and**
 $\text{M-level: cdcl}_W\text{-M-level-inv } S$ **and**
 $\text{no-taut: } \forall s \in \# \text{ learned-clss } S. \neg \text{tautology } s$ **and**
 $\text{no-dup: distinct-cdcl}_W\text{-state } S$ **and**
 $\text{confl: cdcl}_W\text{-conflicting } S$
shows $(\text{cdcl}_W\text{-measure } S', \text{cdcl}_W\text{-measure } S) \in \text{lexn } \{(a, b). a < b\} \text{ } 3$
using *assms(1) M-level assms(2,3)*
proof *(induct rule: cdcl_W-all-induct-lev2)*
case *(propagate C L)* **note** $\text{undef} = \text{this}(3)$ **and** $T = \text{this}(4)$ **and** $\text{conf} = \text{this}(5)$
have $\text{propa: propagate } S \text{ (cons-trail (Propagated L (C + \{\#L\#\})) S)$
using *propagate-rule[OF - propagate.hyps(1,2)] propagate.hyps* **by** *auto*
then have $\text{no-dup': no-dup (Propagated L ((C + \{\#L\#\})) \# \text{trail } S)$
by *(metis M-level cdcl_W-M-level-inv-decomp(2) marked-lit.sel(2) propagate'*
 $\text{r-into-rtranclp rtranclp-cdcl}_W\text{-cp-consistent-inv trail-cons-trail undef})$

let $?N = \text{init-clss } S$
have $\text{no-strange-atm (cons-trail (Propagated L (C + \{\#L\#\})) S)$
using *alien cdcl_W.propagate cdcl_W-no-strange-atm-inv propa M-level* **by** *blast*
then have $\text{atm-of ' lits-of (Propagated L ((C + \{\#L\#\})) \# \text{trail } S)$
 $\subseteq \text{atms-of-msu (init-clss } S)$
using *undef unfolding no-strange-atm-def* **by** *auto*
then have $\text{card (atm-of ' lits-of (Propagated L ((C + \{\#L\#\})) \# \text{trail } S))}$
 $\leq \text{card (atms-of-msu (init-clss } S))$

```

    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  $H$ :  $\text{card } (\text{set-mset } (\{\#D + \{\#L\}\#\} + \text{learned-clss } S))$ 
   $\leq 3 \wedge \text{card } (\text{atms-of-msu } (\{\#D + \{\#L\}\#\} + \text{learned-clss } S))$ 
  using  $T$  undef  $\text{decomp lev}$  by  $(\text{auto simp: cdcl}_W\text{-M-level-inv-decomp})$ 
moreover
  have  $\text{atms-of-msu } (\{\#D + \{\#L\}\#\} + \text{learned-clss } S) \subseteq \text{atms-of-msu } (\text{init-clss } S)$ 
    using  $\text{alien conf unfolding no-strange-atm-def}$  by  $\text{auto}$ 
  then have  $\text{card-f: card } (\text{atms-of-msu } (\{\#D + \{\#L\}\#\} + \text{learned-clss } S))$ 
     $\leq \text{card } (\text{atms-of-msu } (\text{init-clss } S))$ 
    by  $(\text{meson atms-of-ms-finite card-mono finite-set-mset})$ 
  then have  $(3::\text{nat}) \wedge \text{card } (\text{atms-of-msu } (\{\#D + \{\#L\}\#\} + \text{learned-clss } S))$ 
     $\leq 3 \wedge \text{card } (\text{atms-of-msu } (\text{init-clss } S))$  by  $\text{simp}$ 
ultimately have  $(3::\text{nat}) \wedge \text{card } (\text{atms-of-msu } (\text{init-clss } S))$ 
   $\geq \text{card } (\text{set-mset } (\{\#D + \{\#L\}\#\} + \text{learned-clss } S))$ 
  using  $\text{le-trans}$  by  $\text{blast}$ 
then show  $?case$  using  $\text{decomp undef diff-less-mono2 card-T T lev}$ 
  by  $(\text{auto simp: cdcl}_W\text{-M-level-inv-decomp})$ 
next
  case  $\text{restart}$ 
  then show  $?case$  using  $\text{alien by (auto simp: state-eq-def simp del: state-simp)}$ 
next
  case  $(\text{forget } C \ T)$ 
  then have  $C \in \# \text{learned-clss } S$  and  $C \notin \# \text{learned-clss } T$ 
    by  $\text{auto}$ 
  then show  $?case$  using  $\text{forget(9)}$  by  $(\text{simp add: mset-leD})$ 
qed

```

```

lemma  $\text{propagate-measure-decreasing}$ :
  fixes  $S :: 'st$ 
  assumes  $\text{propagate } S \ S'$  and  $\text{cdcl}_W\text{-all-struct-inv } S$ 
  shows  $(\text{cdcl}_W\text{-measure } S', \text{cdcl}_W\text{-measure } S) \in \text{lexn } \{(a, b). a < b\}$   $?$ 
  apply  $(\text{rule cdcl}_W\text{-measure-decreasing})$ 
  using  $\text{assms(1) propagate}$  apply  $\text{blast}$ 
    using  $\text{assms(1) apply (auto simp add: propagate.simps)[3]}$ 
    using  $\text{assms(2) apply (auto simp add: cdcl}_W\text{-all-struct-inv-def)}$ 
  done

```

```

lemma  $\text{conflict-measure-decreasing}$ :
  fixes  $S :: 'st$ 
  assumes  $\text{conflict } S \ S'$  and  $\text{cdcl}_W\text{-all-struct-inv } S$ 
  shows  $(\text{cdcl}_W\text{-measure } S', \text{cdcl}_W\text{-measure } S) \in \text{lexn } \{(a, b). a < b\}$   $?$ 
  apply  $(\text{rule cdcl}_W\text{-measure-decreasing})$ 
  using  $\text{assms(1) conflict}$  apply  $\text{blast}$ 
    using  $\text{assms(1) apply (auto simp add: propagate.simps)[3]}$ 
    using  $\text{assms(2) apply (auto simp add: cdcl}_W\text{-all-struct-inv-def)}$ 
  done

```

```

lemma  $\text{decide-measure-decreasing}$ :
  fixes  $S :: 'st$ 
  assumes  $\text{decide } S \ S'$  and  $\text{cdcl}_W\text{-all-struct-inv } S$ 
  shows  $(\text{cdcl}_W\text{-measure } S', \text{cdcl}_W\text{-measure } S) \in \text{lexn } \{(a, b). a < b\}$   $?$ 
  apply  $(\text{rule cdcl}_W\text{-measure-decreasing})$ 
  using  $\text{assms(1) decide other}$  apply  $\text{blast}$ 
    using  $\text{assms(1) apply (auto simp add: propagate.simps)[3]}$ 
    using  $\text{assms(2) apply (auto simp add: cdcl}_W\text{-all-struct-inv-def)}$ 
  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  $(cdcl_W\text{-measure } S', cdcl_W\text{-measure } S) \in le_{rn} \{(a, b). a < b\} \text{ } 3$ 
  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 trancpl-cdclW-cp-measure-decreasing:
  fixes  $S :: 'st$ 
  assumes cdclW-cp++  $S S'$  and cdclW-all-struct-inv  $S$ 
  shows  $(cdcl_W\text{-measure } S', cdcl_W\text{-measure } S) \in le_{rn} \{(a, b). a < b\} \text{ } 3$ 
  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  $(cdcl_W\text{-measure } T, cdcl_W\text{-measure } S) \in le_{rn} \{a. \text{ case } a \text{ of } (a, b) \Rightarrow a < b\} \text{ } 3$  by blast

  moreover have  $(cdcl_W\text{-measure } U, cdcl_W\text{-measure } T) \in le_{rn} \{a. \text{ case } a \text{ of } (a, b) \Rightarrow a < b\} \text{ } 3$ 
  using cdclW-cp-measure-decreasing[OF step] rtrancpl-cdclW-all-struct-inv-inv  $inv$ 
  trancpl-cdclW-cp-trancpl-cdclW[OF st]
  unfolding trans-def rtrancpl-unfold
  by blast
  ultimately show ?case using lern-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  $(cdcl_W\text{-measure } T, cdcl_W\text{-measure } S) \in le_{rn} \{(a, b). a < b\} \text{ } 3$ 
proof –
  have cdclW-all-struct-inv  $S$ 
  using assms
  by (metis rtrancpl-unfold rtrancpl-cdclW-all-struct-inv-inv trancpl-cdclW-stgy-trancpl-cdclW)
  with assms show ?thesis
  proof induction
  case (conflict'  $V$ ) note  $cp = this(1)$  and  $inv = this(5)$ 
  show ?case
    using trancpl-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 = Some 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-stgy⁺⁺ R S
 trail R = [] and

```

cdclW-all-struct-inv R
shows (cdclW-measure S, cdclW-measure R) ∈ lexn {(a, b). a < b} ?
using assms
apply induction
  using cdclW-stgy-step-decreasing[of R - R] apply blast
using cdclW-stgy-step-decreasing[of - - R] tranclp-into-rtranclp[of cdclW-stgy R]
lexn-transI[OF trans-le, of ?] unfolding trans-def by blast

lemma tranclp-cdclW-stgy-S0-decreasing:
  fixes R S T :: 'st
  assumes pl: cdclW-stgy++ (init-state N) S and
  no-dup: distinct-mset-mset N
  shows (cdclW-measure S, cdclW-measure (init-state N)) ∈ lexn {(a, b). a < b} ?
proof -
  have cdclW-all-struct-inv (init-state N)
    using no-dup unfolding cdclW-all-struct-inv-def by auto
  then show ?thesis using pl tranclp-cdclW-stgy-decreasing init-state-trail by blast
qed

lemma wf-tranclp-cdclW-stgy:
  wf {(S::'st, init-state N) | S N. distinct-mset-mset N ∧ cdclW-stgy++ (init-state N) S}
  apply (rule wf-wf-if-measure'-notation2[of lexn {(a, b). a < b} ? - - cdclW-measure])
  apply (simp add: wf wf-lexn)
  using tranclp-cdclW-stgy-S0-decreasing by blast
end

end
theory DPLL-CDCL-W-Implementation
imports Partial-Annotated-Clausal-Logic
begin

```

18 Simple Implementation of the DPLL and CDCL

18.1 Common Rules

18.1.1 Propagation

The following theorem holds:

```

lemma lits-of-unfold[iff]:
  (∀ c ∈ set C. -c ∈ lits-of Ms) ↔ Ms ⊨as CNot (mset C)
  unfolding true-annots-def Ball-def true-annot-def CNot-def mem-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-unit-clause :: 'a literal list ⇒ ('a, 'b, 'c) marked-lit list ⇒ 'a literal option
where
  is-unit-clause l M =
    (case List.filter (λa. atm-of a ∉ atm-of ' lits-of M) l of
      a # [] ⇒ if M ⊨as CNot (mset l - {#a#}) then Some a else None
      | - ⇒ None)

```

```

definition is-unit-clause-code :: 'a literal list ⇒ ('a, 'b, 'c) marked-lit list
  ⇒ 'a literal option where
  is-unit-clause-code l M =
    (case List.filter (λa. atm-of a ∉ atm-of ' lits-of M) l of
      a # [] ⇒ if (∀ c ∈ set (remove1 a l). -c ∈ lits-of M) then Some a else None

```


| - \Rightarrow None)

lemma *is-unit-clause-is-unit-clause-code*[code]:

is-unit-clause l M = *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 = *Some* a

shows *undefined-lit* M a

proof -

have (case [$a \leftarrow l$. *atm-of* $a \notin \text{atm-of ' lits-of } M$] of [] \Rightarrow None

| [a] \Rightarrow if $M \models_{\text{as}} \text{CNot } (\text{mset } l - \{\#a\# \})$ then *Some* a 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 (cases [$a \leftarrow l$. *atm-of* $a \notin \text{atm-of ' lits-of } M$])

apply *simp*

apply (*rename-tac aa list*; *case-tac list*) **by** (*auto split: split-if-asm*)

hence *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 = *Some* $a \implies M \models_{\text{as}} \text{CNot } (\text{mset } l - \{\#a\# \})$

unfolding *is-unit-clause-def*

proof -

assume (case [$a \leftarrow l$. *atm-of* $a \notin \text{atm-of ' lits-of } M$] of [] \Rightarrow None

| [a] \Rightarrow if $M \models_{\text{as}} \text{CNot } (\text{mset } l - \{\#a\# \})$ then *Some* a else None

| $a \# ab \# xa \Rightarrow \text{Map.empty } xa = \text{Some } a$

thus *?thesis*

apply (cases [$a \leftarrow l$. *atm-of* $a \notin \text{atm-of ' lits-of } M$], *simp*)

apply *simp*

apply (*rename-tac aa list*, *case-tac list*) **by** (*auto split: split-if-asm*)

qed

lemma *is-unit-clause-some-in*: *is-unit-clause* l M = *Some* $a \implies a \in \text{set } l$

unfolding *is-unit-clause-def*

proof -

assume (case [$a \leftarrow l$. *atm-of* $a \notin \text{atm-of ' lits-of } M$] of [] \Rightarrow None

| [a] \Rightarrow if $M \models_{\text{as}} \text{CNot } (\text{mset } l - \{\#a\# \})$ then *Some* a else None

| $a \# ab \# xa \Rightarrow \text{Map.empty } xa = \text{Some } a$

thus $a \in \text{set } l$

by (cases [$a \leftarrow l$. *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  $\models_{\text{as}} \text{CNot } (\text{mset } c - \{\#a\})$  and
undef: undefined-lit M a and
ac: a  $\in \text{set } c$ 
shows is-unit-clause c M  $\neq$  None

```

proof –

```

have [a  $\leftarrow$  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 +  $\{\#ac\} - \{\#a\} = \text{mset } c - \{\#a\} + \{\#ac\}$ 
  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  $\implies c \in \text{set } l \implies M \models_{\text{as}} \text{CNot } (\text{mset } c - \{\#a\}) \implies \text{undefined-lit } M a \implies a \in \text{set } c$ 
 $\implies \text{find-first-unit-clause } l M \neq \text{None}$ 
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* ($\lambda lit. lit \notin M \wedge -lit \notin M$) *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 ($\lambda lit. lit \notin M \wedge -lit \notin M$) *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* ($\lambda lit. lit \notin M \wedge -lit \notin M$) *a* = Some *b* $\implies b \in \text{set } a \wedge b \notin M \wedge -b \notin M$
unfolding *find-Some-iff* **by** (*metis nth-mem*)

lemma *find-first-unused-var-None*[*iff*]:

find-first-unused-var *l* *M* = None $\longleftrightarrow (\forall a \in \text{set } l. \text{atm-of ' set } a \subseteq \text{atm-of ' } M)$
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 $\neg(\forall a \in \text{set } l. \text{atm-of ' set } a \subseteq \text{atm-of ' } M)$

proof –

have *find-first-unused-var* *l* *M* \neq None
using *assms* **by** (*cases find-first-unused-var l M*) *auto*
thus $\neg(\forall a \in \text{set } l. \text{atm-of ' set } a \subseteq \text{atm-of ' } M)$ **by** *auto*

qed

lemma *find-first-unused-var-Some*:

find-first-unused-var *l* *M* = Some *a* $\implies (\exists m \in \text{set } l. a \in \text{set } m \wedge a \notin M \wedge -a \notin M)$
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* $\implies \text{undefined-lit } Ms \ a$
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-step* :: int *dpll_W-marked-lits* \times int literal list list

\Rightarrow int *dpll_W-marked-lits* \times int literal list list **where**

DPLL-step = ($\lambda(Ms, N).$

```

(case find-first-unit-clause N Ms of
  Some (L, -) ⇒ (Propagated L () # Ms, N)
| - ⇒
  if ∃ C ∈ set N. (∀ c ∈ set C. -c ∈ lits-of Ms)
  then
    (case backtrack-split Ms of
      (-, L # M) ⇒ (Propagated (- (lit-of L)) () # M, N)
    | (-, -) ⇒ (Ms, N)
    )
  else
    (case find-first-unused-var N (lits-of Ms) of
      Some a ⇒ (Marked a () # Ms, N)
    | None ⇒ (Ms, N))))

```

Example of propagation:

```

value DPLL-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 ≡ λ(Ms::(int, unit, unit) marked-lit list)
  (N:: int literal list list). (Ms, mset (map mset N))
abbreviation toS' ≡ λ(Ms::(int, unit, unit) marked-lit list,
  N:: int literal list list). (Ms, mset (map mset N))

```

Proof of correctness of *DPLL-step*

lemma *DPLL-step-is-a-dpll_W-step*:

```

assumes step: (Ms', N') = DPLL-step (Ms, N)
and neg: (Ms, N) ≠ (Ms', N')
shows dpllW (toS Ms N) (toS Ms' N')

```

proof –

```

let ?S = (Ms, mset (map mset N))
{ fix L E
  assume unit: find-first-unit-clause N Ms = Some (L, E)
  hence Ms'N: (Ms', N') = (Propagated L () # Ms, N)
    using step unfolding DPLL-step-def by auto
  obtain C where
    C: C ∈ set N and
    Ms: Ms ⊨as CNot (mset C - {#L#}) and
    undef: undefined-lit Ms L and
    L ∈ set C using find-first-unit-clause-some[OF unit] by metis
  have dpllW (Ms, mset (map mset N))
    (Propagated L () # fst (Ms, mset (map mset N)), snd (Ms, mset (map mset N)))
    apply (rule dpllW.propagate)
    using Ms undef C (L ∈ set C) unfolding mem-set-multiset-eq by (auto simp add: C)
  hence ?thesis using Ms'N by auto
}

```

moreover

```

{ assume unit: find-first-unit-clause N Ms = None
  assume exC: ∃ C ∈ set N. Ms ⊨as CNot (mset C)
  then obtain C where C: C ∈ set N and Ms: Ms ⊨as CNot (mset C) by auto
  then obtain L M M' where bt: backtrack-split Ms = (M', L # M)
    using step exC neg unfolding DPLL-step-def prod.case unit
    by (cases backtrack-split Ms, rename-tac b, case-tac b) auto
  hence is-marked L using backtrack-split-snd-hd-marked[of Ms] by auto
  have 1: dpllW (Ms, mset (map mset N))

```

```

      (Propagated (– lit-of L) () # M, snd (Ms, mset (map mset N)))
    apply (rule dpllW.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: ¬ (∃ C ∈ set N. Ms ⊨as CNot (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 dpllW (Ms, mset (map mset N))
    (Marked L () # fst (Ms, mset (map mset N)), snd (Ms, mset (map mset N)))
    apply (rule dpllW.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-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: ∃ C ∈ set N. Ms ⊨_{as} CNot (mset C)
 hence Ms: (Ms, N) = (case backtrack-split Ms of (x, []) ⇒ (Ms, N)
 | (x, L # M) ⇒ (Propagated (– lit-of L) () # M, N))
 using step unfolding DPLL-step-def by (simp add: unit)

have snd (backtrack-split Ms) = []

proof (cases backtrack-split Ms, cases snd (backtrack-split Ms))

fix a b

assume backtrack-split Ms = (a, b) and snd (backtrack-split Ms) = []

thus snd (backtrack-split Ms) = [] by blast

next

fix a b aa list

assume

bt: backtrack-split Ms = (a, b) and

bt': snd (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:  $\neg (\exists C \in \text{set } N. Ms \models_{as} CNot (mset C))$ 
  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:  $\forall a \in \text{set } N. atm\text{-of } 'set\ a \subseteq atm\text{-of } ' (lits\text{-of } Ms)$  by auto
  have fst (toS Ms N)  $\models_{asm}$  snd (toS Ms N) unfolding true-annots-def CNot-def Ball-def
  proof clarify
    fix x
    assume x:  $x \in \text{set-mset } (clauses (toS Ms N))$ 
    hence  $\neg Ms \models_{as} CNot\ x$  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)  $\models_a$  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 \Rightarrow int literal list list`

```

 $\Rightarrow$  int dpllW-marked-lits  $\times$  int literal list list where
DPLL-ci Ms N =
  (if  $\neg dpll_W\text{-all-inv } (Ms, mset (map mset N))$ 
   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)  $\in$  {(S', S). dpllW-all-inv S  $\wedge$  dpllW S S'}})
  show wf {(S', S). (toS' S', toS' S)  $\in$  {(S', S). dpllW-all-inv S  $\wedge$  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  $\neg \neg dpll_W\text{-all-inv } (toS Ms N)$ 
  and step: x = DPLL-step (Ms, N)
  and x: (xa, y) = x
  and (xa, y)  $\neq$  (Ms, N)
  thus ((xa, N), Ms, N)  $\in$  {(S', S). (toS' S', toS' S)  $\in$  {(S', S). dpllW-all-inv S  $\wedge$  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 dpllW-marked-lits \Rightarrow int literal list list`

```

 $\Rightarrow$ 
  int dpllW-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 $DPLL\text{-}part\ Ms'\ N$
 by fast+

lemma *snd-DPLL-step[simp]*:

snd ($DPLL\text{-}step\ (Ms, N)$) = N

unfolding $DPLL\text{-}step\text{-}def$ **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 $DPLL\text{-}ci\ Ms\ N = DPLL\text{-}part\ Ms\ N \wedge DPLL\text{-}part\text{-}dom\ (Ms, N)$

using *assms*

proof (*induct rule: DPLL-ci.induct*)

case (1 $Ms\ N$)

have *snd* ($DPLL\text{-}step\ (Ms, N)$) = N **by** *auto*

then obtain Ms' **where** Ms' : $DPLL\text{-}step\ (Ms, N) = (Ms', N)$ **by** (*cases 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 $DPLL\text{-}ci\ Ms'\ N = DPLL\text{-}part\ Ms'\ N \wedge DPLL\text{-}part\text{-}dom\ (Ms', N)$ **using** $1(1)[of - Ms'\ N]$

Ms'

$1(2)$ *inv'* **by** *auto*

hence $DPLL\text{-}part\text{-}dom\ (Ms, N)$ **using** $DPLL\text{-}part\text{-}dom\text{intros}\ Ms'$ **by** *fastforce*

moreover have $DPLL\text{-}ci\ Ms\ N = DPLL\text{-}part\ Ms\ N$ **using** $1.prem\ DPLL\text{-}part.psims\ Ms'$

$\langle DPLL\text{-}ci\ Ms'\ N = DPLL\text{-}part\ Ms'\ N \wedge DPLL\text{-}part\text{-}dom\ (Ms', N) \rangle \langle DPLL\text{-}part\text{-}dom\ (Ms, N) \rangle$ **by**

auto

ultimately have *?case* **by** *blast*

}

moreover {

assume $(Ms', N) = (Ms, N)$

hence *?case* **using** $DPLL\text{-}part\text{-}dom\text{intros}\ DPLL\text{-}part.psims\ Ms'$ **by** *fastforce*

}

ultimately show *?case* **by** *blast*

qed

lemma *DPLL-ci-dpll_W-rtrancp*:

assumes $DPLL\text{-}ci\ Ms\ N = (Ms', N')$

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** $S: (S_1, S_2) = DPLL\text{-}step\ (Ms, N)$ **by** (*cases DPLL-step (Ms, N)*) *auto*

{ **assume** $\neg dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N)$

hence $(Ms, N) = (Ms', N)$ **using** *step* **by** *auto*

hence *?case* **by** *auto*

}

moreover

{ **assume** $dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N)$

and $(S_1, S_2) = (Ms, N)$

hence *?case* **using** $S\ step$ **by** *auto*

}

moreover

{ **assume** $dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N)$

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** (*cases DPLL-ci S₁ 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 $(metis\ DPLL\text{-}step\text{-}is\text{-}a\text{-}dpll_W\text{-}step\ S\ \langle(S_1, S_2) \neq (Ms, N)\rangle\ prod.sel(2)\ snd\text{-}DPLL\text{-}step)$
ultimately have *?case* **by** $(metis\ (mono\text{-}tags,\ hide\text{-}lams)\ IH\ S\ \langle(S_1, S_2) \neq (Ms, N)\rangle$
 $\langle DPLL\text{-}ci\ Ms\ N = DPLL\text{-}ci\ S_1\ N \rangle\ \langle dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N) \rangle\ converse\text{-}rtranclp\text{-}into\text{-}rtranclp$
 $local.step)$
}
ultimately show *?case* **by** *blast*
qed

lemma $dpll_W\text{-}all\text{-}inv\text{-}dpll_W\text{-}tranclp\text{-}irrefl$:
 assumes $dpll_W\text{-}all\text{-}inv\ (Ms, N)$
 and $dpll_W^{++}\ (Ms, N)\ (Ms, N)$
 shows *False*
proof –
 have $1: wf\ \{(S', S). dpll_W\text{-}all\text{-}inv\ S \wedge dpll_W^{++}\ S\ S'\}$ **using** $dpll_W\text{-}wf\text{-}tranclp$ **by** *auto*
 have $((Ms, N), (Ms, N)) \in \{(S', S). dpll_W\text{-}all\text{-}inv\ S \wedge dpll_W^{++}\ S\ S'\}$ **using** *assms* **by** *auto*
 thus *False* **using** $wf\text{-}not\text{-}refl[OF\ 1]$ **by** *blast*
qed

lemma $DPLL\text{-}ci\text{-}final\text{-}state$:
 assumes $step: DPLL\text{-}ci\ Ms\ N = (Ms, N)$
 and $inv: dpll_W\text{-}all\text{-}inv\ (toS\ Ms\ N)$
 shows $conclusive\text{-}dpll_W\text{-}state\ (toS\ Ms\ N)$
proof –
 have $st: dpll_W^{**}\ (toS\ Ms\ N)\ (toS\ Ms\ N)$ **using** $DPLL\text{-}ci\text{-}dpll_W\text{-}rtranclp[OF\ step]$.
 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 $(cases\ DPLL\text{-}step\ (Ms, N))\ auto$
 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 $(metis\ DPLL\text{-}ci\text{-}dpll_W\text{-}rtranclp\ DPLL\text{-}step\text{-}is\text{-}a\text{-}dpll_W\text{-}step\ Ms'\ N\ \langle DPLL\text{-}step\ (Ms, N) \neq (Ms,$
 $N) \rangle$
 $prod.sel(2)\ rtranclp\text{-}into\text{-}tranclp2\ snd\text{-}DPLL\text{-}step)$
 thus *False* **using** $dpll_W\text{-}all\text{-}inv\text{-}dpll_W\text{-}tranclp\text{-}irrefl\ inv$ **by** *auto*
qed
 thus *?thesis* **using** $DPLL\text{-}step\text{-}stuck\text{-}final\text{-}state[of\ Ms\ N]$ **by** *simp*
qed

lemma $DPLL\text{-}step\text{-}obtains$:
 obtains Ms' **where** $(Ms', N) = DPLL\text{-}step\ (Ms, N)$
 unfolding $DPLL\text{-}step\text{-}def$ **by** $(metis\ (no\text{-}types,\ lifting)\ DPLL\text{-}step\text{-}def\ prod.collapse\ snd\text{-}DPLL\text{-}step)$

lemma *DPLL-ci-obtains*:

obtains Ms' **where** $(Ms', N) = \text{DPLL-ci } Ms \ N$

proof (*induct rule: DPLL-ci.induct*)

case $(1 \ Ms \ N)$ **note** $IH = \text{this}(1)$ **and** $\text{that} = \text{this}(2)$

obtain S **where** $SN: (S, N) = \text{DPLL-step } (Ms, N)$ **using** *DPLL-step-obtains* **by** *metis*

{ **assume** $\neg \text{dpll}_W\text{-all-inv } (\text{toS } Ms \ N)$

hence *?case* **using** *that* **by** *auto*

}

moreover {

assume $n: (S, N) \neq (Ms, N)$

and $\text{inv}: \text{dpll}_W\text{-all-inv } (\text{toS } Ms \ N)$

have $\exists ms. \text{DPLL-step } (Ms, N) = (ms, N)$

by (*metis* $\langle \bigwedge \text{thesis}. (\bigwedge S. (S, N) = \text{DPLL-step } (Ms, N) \implies \text{thesis}) \implies \text{thesis} \rangle$)

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*: $\text{DPLL-ci } Ms \ N = (Ms', N')$

shows $\text{DPLL-ci } Ms' \ N' = (Ms', N')$

using *assms*

proof (*induct arbitrary: Ms' N' rule: DPLL-ci.induct*)

case $(1 \ Ms \ N \ Ms' \ N')$ **note** $IH = \text{this}(1)$ **and** $\text{step} = \text{this}(2)$

obtain S_1 **where** $S: (S_1, N) = \text{DPLL-step } (Ms, N)$ **using** *DPLL-step-obtains* **by** *auto*

{ **assume** $\neg \text{dpll}_W\text{-all-inv } (\text{toS } Ms \ N)$

hence *?case* **using** *step* **by** *auto*

}

moreover {

assume $\text{dpll}_W\text{-all-inv } (\text{toS } Ms \ N)$

and $(S_1, N) = (Ms, N)$

hence *?case* **using** *S step* **by** *auto*

}

moreover

{ **assume** $\text{inv}: \text{dpll}_W\text{-all-inv } (\text{toS } Ms \ N)$

assume $n: (S_1, N) \neq (Ms, N)$

obtain S_1' **where** $SS: (S_1', N) = \text{DPLL-ci } S_1 \ N$ **using** *DPLL-ci-obtains* **by** *blast*

moreover have $\text{DPLL-ci } Ms \ N = \text{DPLL-ci } S_1 \ N$

proof –

have (*case* (S_1, N) *of* $(ms, lss) \Rightarrow$ *if* $(ms, lss) = (Ms, N)$ *then* (Ms, N) *else* $\text{DPLL-ci } ms \ N$)
 $= \text{DPLL-ci } Ms \ N$

using *S DPLL-ci.simps[of Ms N]* *calculation inv* **by** *presburger*

hence (*if* $(S_1, N) = (Ms, N)$ *then* (Ms, N) *else* $\text{DPLL-ci } S_1 \ N = \text{DPLL-ci } Ms \ N$)

by *fastforce*

thus *?thesis*

using *calculation n* **by** *presburger*

qed

moreover

```

    have DPLL-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*: *dpll_W-all-inv* (*Ms*, *mset* (*map mset N*))

and *MsN*: *DPLL-part* *Ms N* = (*Ms'*, *N*)

shows *conclusive-dpll_W-state* (*toS Ms' N*) \wedge *dpll_W*** (*toS Ms N*) (*toS Ms' N*)

proof –

have 2: *DPLL-ci* *Ms N* = *DPLL-part* *Ms N* **using** *inv dpll_W-all-inv-implicS-2-eq3-and-dom* **by** *blast*

hence *star*: *dpll_W*** (*toS Ms N*) (*toS Ms' N*) **unfolding** *MsN* **using** *DPLL-ci-dpll_W-rtranclp* **by**

blast

hence *inv'*: *dpll_W-all-inv* (*toS Ms' N*) **using** *inv rtranclp-dpll_W-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** *dpll_W-state* =

{(*M*::(*int*, *unit*, *unit*) *marked-lit list*, *N*::*int literal list list*).

dpll_W-all-inv (*toS M N*)}

morphisms *rough-state-of state-of*

proof

show (\square, \square) $\in \{(M, N). \text{dpll}_W\text{-all-inv } (toS\ M\ N)\}$ **by** (*auto simp add: dpll_W-all-inv-def*)

qed

lemma

DPLL-part-dom (\square, N)

using *assms dpll_W-all-inv-implicS-2-eq3-and-dom*[*of* $\square\ N$] **by** (*simp add: dpll_W-all-inv-def*)

Some type classes **instantiation** *dpll_W-state* :: *equal*

begin

definition *equal-dpll_W-state* :: *dpll_W-state* \Rightarrow *dpll_W-state* \Rightarrow *bool* **where**

equal-dpll_W-state *S S'* = (*rough-state-of S* = *rough-state-of S'*)

instance

by *standard* (*simp add: rough-state-of-inject equal-dpll_W-state-def*)

end

DPLL **definition** *DPLL-step'* :: *dpll_W-state* \Rightarrow *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*) $\in \{(M, N). \text{dpll}_W\text{-all-inv } (toS\ M\ N)\}$

by (*smt DPLL-ci.simps DPLL-ci-dpll_W-rtranclp case-prodE case-prodI2 rough-state-of mem-Collect-eq old.prod.case prod.sel(2) rtranclp-dpll_W-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-step' S = S)
apply simp
unfolding DPLL-tot.simps[of S] by (simp del: DPLL-tot.simps)

lemma DOPLL-step'-DPLL-tot[simp]:

```

$DPLL\text{-}step' (DPLL\text{-}tot S) = DPLL\text{-}tot S$
by (rule $DPLL\text{-}tot.induct[of \lambda S. DPLL\text{-}step' (DPLL\text{-}tot S) = DPLL\text{-}tot S S]$)
 (metis (full-types) $DPLL\text{-}tot.simps$)

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** $assms[symmetric]$ $DOPLL\text{-}step'\text{-}DPLL\text{-}tot$ **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 $rough\text{-}state\text{-}of\text{-}DPLL\text{-}step'\text{-}DPLL\text{-}step$)
thus $?thesis$
by (metis (mono-tags, lifting) $DPLL\text{-}step\text{-}stuck\text{-}final\text{-}state$ $old.prod.exhaust$ $split\text{-}conv$)

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: $DPLL\text{-}tot.induct$)

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 $DPLL\text{-}step\text{-}is\text{-}a\text{-}dpll_W\text{-}step$ $DPLL\text{-}tot.simps$ $case\text{-}prodE2$
 $rough\text{-}state\text{-}of\text{-}DPLL\text{-}step'\text{-}DPLL\text{-}step$ $rtranclp.rtrancl\text{-}into\text{-}rtrancl$ $rtranclp.rtrancl\text{-}refl$
 $rtranclp\text{-}idemp$ $split\text{-}conv$)

}

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 $DPLL\text{-}W\text{-}Implementation.dpll_W\text{-}state.state\text{-}of\text{-}inverse$)

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 $M' \models_{asm} N'' \longleftrightarrow satisfiable (set\text{-}mset N'')$

proof –

have $dpll_W^{**} (toS' ([], N)) (toS' (M, N'))$ **using** $DPLL\text{-}tot\text{-}star[OF assms(1)]$ **by** $auto$

moreover have $conclusive\text{-}dpll_W\text{-}state (toS' (M, N'))$

using $DPLL\text{-}tot\text{-}final\text{-}state$ **by** (metis (mono-tags, lifting) $DOPLL\text{-}step'\text{-}DPLL\text{-}tot$ $DPLL\text{-}tot.simps$
 $assms(1)$)

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) marked-lit*
list × int 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 ([], []))

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 (∀ A ∈ set N. (∃ a ∈ set A. a ∈ 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 option

abbreviation *trail :: 'a × 'b × 'c × 'd × 'e ⇒ 'a* **where**

trail ≡ (λ(M, -). M)

abbreviation *cons-trail* :: 'a \Rightarrow 'a list \times 'b \times 'c \times 'd \times 'e \Rightarrow 'a list \times 'b \times 'c \times 'd \times 'e
where
cons-trail $\equiv (\lambda L (M, S). (L \# M, S))$

abbreviation *tl-trail* :: 'a list \times 'b \times 'c \times 'd \times 'e \Rightarrow 'a list \times 'b \times 'c \times 'd \times 'e **where**
tl-trail $\equiv (\lambda (M, S). (tl\ M, S))$

abbreviation *clss* :: 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'b **where**
clss $\equiv \lambda (M, N, -). N$

abbreviation *learned-clss* :: 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'c **where**
learned-clss $\equiv \lambda (M, N, U, -). U$

abbreviation *backtrack-lvl* :: 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'd **where**
backtrack-lvl $\equiv \lambda (M, N, U, k, -). k$

abbreviation *update-backtrack-lvl* :: 'd \Rightarrow 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'a \times 'b \times 'c \times 'd \times 'e
where
update-backtrack-lvl $\equiv \lambda k (M, N, U, -, S). (M, N, U, k, S)$

abbreviation *conflicting* :: 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'e **where**
conflicting $\equiv \lambda (M, N, U, k, D). D$

abbreviation *update-conflicting* :: 'e \Rightarrow 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'a \times 'b \times 'c \times 'd \times 'e
where
update-conflicting $\equiv \lambda S (M, N, U, k, -). (M, N, U, k, S)$

abbreviation *S0-cdcl_W* *N* $\equiv (([], N, \{\#\}, 0, None) :: 'v\ cdcl_W\text{-state})$

abbreviation *add-learned-clss* **where**
add-learned-clss $\equiv \lambda C (M, N, U, S). (M, N, \{\#C\# \} + U, S)$

abbreviation *remove-clss* **where**
remove-clss $\equiv \lambda C (M, N, U, S). (M, remove\text{-mset}\ C\ N, remove\text{-mset}\ C\ U, S)$

lemma *trail-conv*: *trail* (M, N, U, k, D) = M **and**
clauses-conv: *clss* (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 = (*trail* *S*, *clss* *S*, *learned-clss* *S*, *backtrack-lvl* *S*, *conflicting* *S*)
by (*cases* *S*) *auto*

interpretation *state_W* *trail* *clss* *learned-clss* *backtrack-lvl* *conflicting*
 $\lambda L (M, S). (L \# M, S)$
 $\lambda (M, S). (tl\ M, S)$
 $\lambda C (M, N, S). (M, \{\#C\# \} + N, S)$
 $\lambda C (M, N, U, S). (M, N, \{\#C\# \} + U, S)$
 $\lambda C (M, N, U, S). (M, remove\text{-mset}\ C\ N, remove\text{-mset}\ C\ U, S)$
 $\lambda (k :: nat) (M, N, U, -, D). (M, N, U, k, D)$
 $\lambda D (M, N, U, k, -). (M, N, U, k, D)$

$\lambda N. ([], N, \{\#\}, 0, \text{None})$
 $\lambda(-, N, U, -). ([], N, U, 0, \text{None})$
by *unfold-locales auto*

interpretation *cdcl_W trail clss learned-clss backtrack-lvl conflicting*

$\lambda L (M, S). (L \# M, S)$
 $\lambda(M, S). (tl\ M, S)$
 $\lambda C (M, N, S). (M, \{\#C\# \} + N, S)$
 $\lambda C (M, N, U, S). (M, N, \{\#C\# \} + U, S)$
 $\lambda C (M, N, U, S). (M, \text{remove-mset } C\ N, \text{remove-mset } C\ U, S)$
 $\lambda(k::nat) (M, N, U, -, D). (M, N, U, k, D)$
 $\lambda D (M, N, U, k, -). (M, N, U, k, D)$
 $\lambda N. ([], N, \{\#\}, 0, \text{None})$
 $\lambda(-, N, U, -). ([], N, U, 0, \text{None})$
by *unfold-locales auto*

declare *clauses-def[simp]*

lemma *cdcl_W-state-eq-equality[iff]*: *state-eq S T \longleftrightarrow S = T*

unfolding *state-eq-def* **by** (*cases S, cases T*) *auto*

declare *state-simp[simp del]*

18.3 CDCL Implementation

18.3.1 Definition of the rules

Types **lemma** *true-clss-remdups[simp]*:

$I \models s (mset \circ \text{remdups}) \text{ ' } N \longleftrightarrow I \models s mset \text{ ' } N$
by (*simp add: true-clss-def*)

lemma *satisfiable-mset-remdups[simp]*:

satisfiable ((mset \circ remdups) ' N) \longleftrightarrow satisfiable (mset ' N)

unfolding *satisfiable-carac[symmetric]* **by** *simp*

value *backtrack-split* [*Marked (Pos (Suc 0)) ()*]

value $\exists C \in \text{set } [[\text{Pos } (Suc\ 0), \text{Neg } (Suc\ 0)]] . (\forall c \in \text{set } C. -c \in \text{lits-of } [\text{Marked } (Pos\ (Suc\ 0))\ ()])$

type-synonym *cdcl_W-state-inv-st* = (*nat, nat, nat literal list*) *marked-lit list* \times

nat literal list list \times *nat literal list list* \times *nat* \times *nat literal list option*

We need some functions to convert between our abstract state *nat cdcl_W-state* and the concrete state *cdcl_W-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

abbreviation *convertC* :: *'a list option* \Rightarrow *'a multiset option* **where**

convertC \equiv *map-option mset*

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 (map convert M) n x = get-rev-level M n x

by (*induction M arbitrary: n rule: marked-lit-list-induct*) *auto*

lemma *get-level-map-convert*[simp]:
get-level (map convert *M*) = *get-level* *M*
using *get-rev-level-map-convert*[of rev *M*] **by** (*simp* add: *rev-map*)

lemma *get-maximum-level-map-convert*[simp]:
get-maximum-level (map convert *M*) *D* = *get-maximum-level* *M* *D*
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 ([], [], [], 0, None) \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*, None)) (*toS* (*Propagated* *L* *C* # *M*, *N*, *U*, *k*, None))
using *assms*
by (auto *dest*!: *find-first-unit-clause-some simp* add: *propagate.simps*
intro!: *exI*[of - *mset* *C* - {#*L*#}])

18.3.2 The Transitions

Propagate **definition** *do-propagate-step* **where**

```
do-propagate-step S =
  (case S of
    (M, N, U, k, None) =>
      (case find-first-unit-clause (N @ U) M of
        Some (L, C) => (Propagated L C # M, N, U, k, None)
      | None => (M, N, U, k, None))
  | S => S)
```

lemma *do-propagate-step*:

```
do-propagate-step S ≠ S ==> propagate (toS S) (toS (do-propagate-step S))
apply (cases S, cases conflicting S)
using find-first-unit-clause-some-is-propagate[of clss S learned-clss S trail S - -
  backtrack-lvl S]
by (auto simp add: do-propagate-step-def split: option.splits)
```

lemma *do-propagate-step-option*[simp]:

```
conflicting S ≠ None ==> 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: ∀ c∈set (clss S @ 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, None) and
  T: T = (Propagated L (C + {#L#}) # M, N, U, k, None) and
  MC: M ⊨as CNot C and
  undef: undefined-lit M L and
  CL: C + {#L#} ∈# N + U
apply - by (cases toS S) auto
```

```
let ?M = trail S
let ?N = clss S
let ?U = learned-clss S
let ?k = backtrack-lvl S
let ?D = None
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  $find-first-unit-clause\ (?N\ @\ ?U)\ ?M \neq None$ 
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
 $find-conflict\ M\ [] = None$  |
 $find-conflict\ M\ (N \# Ns) = (if\ (\forall c \in set\ Ns.\ \neg c \in lits-of\ M)\ then\ Some\ N\ else\ find-conflict\ M\ Ns)$ 

```

```

lemma  $find-conflict-Some$ :
 $find-conflict\ M\ Ns = Some\ N \implies N \in set\ Ns \wedge M \models_{as} CNot\ (mset\ N)$ 
by ( $induction\ Ns\ rule: find-conflict.induct$ )
  ( $auto\ split: split-if-asm$ )

```

```

lemma  $find-conflict-None$ :
 $find-conflict\ M\ Ns = None \iff (\forall N \in set\ Ns.\ \neg M \models_{as} CNot\ (mset\ N))$ 
by ( $induction\ Ns$ )  $auto$ 

```

```

lemma  $find-conflict-None-no-conflict$ :
 $find-conflict\ M\ (N @ U) = None \iff no-step\ conflict\ (toS\ (M,\ N,\ U,\ k,\ None))$ 
by ( $auto\ simp\ add: find-conflict-None\ conflict.simps$ )

```

```

definition  $do-conflict-step$  where
 $do-conflict-step\ S =$ 
  ( $case\ S\ of$ 
    ( $M,\ N,\ U,\ k,\ None$ )  $\Rightarrow$ 
      ( $case\ find-conflict\ M\ (N @ U)\ of$ 
         $Some\ a \Rightarrow (M,\ N,\ U,\ k,\ Some\ a)$ 
        |  $None \Rightarrow (M,\ N,\ U,\ k,\ None)$ )
    |  $S \Rightarrow S$ )

```

```

lemma  $do-conflict-step$ :
 $do-conflict-step\ S \neq S \implies conflict\ (toS\ S)\ (toS\ (do-conflict-step\ S))$ 
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  $find-conflict-None-no-conflict[of\ trail\ S\ class\ S\ learned-class\ S]$ 
   $backtrack-lvl\ S$ 
by ( $auto\ split: option.splits$ )

```

```

lemma  $do-conflict-step-option[simp]$ :

```

$\text{conflicting } S \neq \text{None} \implies \text{do-conflict-step } S = S$
unfolding $\text{do-conflict-step-def}$ **by** (cases S , cases $\text{conflicting } S$) *auto*

lemma $\text{do-conflict-step-conflicting[dest]}$:
 $\text{do-conflict-step } S \neq S \implies \text{conflicting } (\text{do-conflict-step } S) \neq \text{None}$
unfolding $\text{do-conflict-step-def}$ **by** (cases S , cases $\text{conflicting } S$) (*auto split: option.splits*)

definition do-cp-step **where**
 $\text{do-cp-step } S =$
 $(\text{do-propagate-step } o \text{ do-conflict-step}) S$

lemma $\text{cp-step-is-cdcl}_W\text{-cp}$:
assumes H : $\text{do-cp-step } S \neq S$
shows $\text{cdcl}_W\text{-cp}$ ($\text{toS } S$) ($\text{toS } (\text{do-cp-step } S)$)
proof –
show ?thesis
proof (cases $\text{do-conflict-step } S \neq S$)
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] : $\text{do-conflict-step } S = S$ **by** *simp*
show ?thesis
proof (cases $\text{do-propagate-step } S = S$)
case *True*
then show ?thesis
using H **by** (*simp add: do-cp-step-def*)
next
case *False*
let ? $S = \text{toS } S$
let ? $T = \text{toS } (\text{do-propagate-step } S)$
let ? $U = \text{toS } (\text{do-conflict-step } (\text{do-propagate-step } S))$
have *propa*: $\text{propagate } (\text{toS } S) \text{ ?}T$ **using** *False do-propagate-step* **by** *blast*
moreover have *ns*: $\text{no-step conflict } (\text{toS } S)$ **using** *confl do-conflict-step-no-step* **by** *blast*
ultimately show ?thesis
using $\text{cdcl}_W\text{-cp.intros}(2)$ [*of ?S ?T*] *confl* **unfolding** do-cp-step-def **by** *auto*
qed
qed
qed

lemma $\text{do-cp-step-eq-no-prop-no-confl}$:
 $\text{do-cp-step } S = S \implies \text{do-conflict-step } S = S \wedge \text{do-propagate-step } S = S$
by (cases S , cases $\text{conflicting } S$)
 $(\text{auto simp add: do-conflict-step-def do-propagate-step-def do-cp-step-def split: option.splits})$

lemma $\text{no-cdcl}_W\text{-cp-iff-no-propagate-no-conflict}$:
 $\text{no-step cdcl}_W\text{-cp } S \iff \text{no-step propagate } S \wedge \text{no-step conflict } S$
by (*auto simp: cdcl_W-cp.simps*)

lemma $\text{do-cp-step-eq-no-step}$:
assumes H : $\text{do-cp-step } S = S$ **and** $\forall c \in \text{set } (\text{class } S @ \text{learned-clss } S)$. *distinct c*
shows $\text{no-step cdcl}_W\text{-cp}$ ($\text{toS } S$)
unfolding $\text{no-cdcl}_W\text{-cp-iff-no-propagate-no-conflict}$
using *assms* **apply** (cases S , cases $\text{conflicting } S$)

```

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 cdclW-cp-cdclW-st: cdclW-cp S S'  $\implies$  cdclW** S S'
by (simp add: cdclW-cp-tranclp-cdclW tranclp-into-rtranclp)

lemma cdclW-cp-wf-all-inv:
  wf {(S', S::'v::linorder cdclW-state). cdclW-all-struct-inv S  $\wedge$  cdclW-cp S S'}
  (is wf ?R)
proof (rule wf-bounded-measure[of -  $\lambda S$ . card (atms-of-msu (clss S))+1
   $\lambda S$ . length (trail S) + (if conflicting S = None then 0 else 1)], goal-cases)
case (1 S S')
then have cdclW-all-struct-inv S and cdclW-cp S S' by auto
moreover then have cdclW-all-struct-inv S'
  using rtranclp-cdclW-all-struct-inv-inv cdclW-cp-cdclW-st by blast
ultimately show ?case
  by (auto simp:cdclW-cp.simps elim!: conflictE propagateE
    dest: length-model-le-vars-all-inv)
qed

lemma cdclW-all-struct-inv-rough-state[simp]: cdclW-all-struct-inv (toS (rough-state-of S))
  using rough-state-of by auto

lemma [simp]: cdclW-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 cdclW-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-cdclW-cp[of rough-state-of S] cdclW-all-struct-inv-rough-state[of S]
    cdclW-cp-cdclW-st rtranclp-cdclW-all-struct-inv-inv by blast
  then show ?thesis by auto
qed

Skip fun do-skip-step :: cdclW-state-inv-st  $\Rightarrow$  cdclW-state-inv-st where
do-skip-step (Propagated L C # Ls,N,U,k, Some D) =
  (if  $-L \notin \text{set } D \wedge D \neq []$ 
  then (Ls, N, U, k, Some D)
  else (Propagated L C # Ls, N, U, k, Some D)) |
do-skip-step S = S

lemma do-skip-step:
  do-skip-step S  $\neq$  S  $\implies$  skip (toS S) (toS (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  $\implies$  no-step skip (toS S)
  by (induction S rule: do-skip-step.induct)
  (auto simp add: other split: split-if-asm)

```

lemma *do-skip-step-trail-is-None*[iff]:

do-skip-step $S = (a, b, c, d, \text{None}) \longleftrightarrow S = (a, b, c, d, \text{None})$

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 ($L \# Ls$) $M = \max$ (*get-level* M L) (*maximum-level-code* Ls M)

lemma *maximum-level-code-eq-get-maximum-level*[code, simp]:

maximum-level-code D $M = \text{get-maximum-level}$ M (*mset* D)

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 , *Some* D) =

(*if* $-L \in \text{set } D \wedge \text{maximum-level-code} (\text{remove1 } (-L) D) (\text{Propagated } L C \# Ls) = k$
then (Ls , N , U , k , *Some* (*remdups* (*remove1* L C @ *remove1* $(-L) D$)))
else (*Propagated* L $C \# Ls$, N , U , k , *Some* D)) |

do-resolve-step $S = S$

lemma *do-resolve-step*:

cdcl_W-all-struct-inv (*toS* S) \Longrightarrow *do-resolve-step* $S \neq S$

\Longrightarrow *resolve* (*toS* S) (*toS* (*do-resolve-step* S))

proof (*induction* S *rule*: *do-resolve-step.induct*)

case ($1 L C M N U k D$)

then have

– $L \in \text{set } D$ **and**

M : *maximum-level-code* (*remove1* $(-L) D$) (*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*) +

have *every-mark-is-a-conflict* (*toS* (*Propagated* L $C \# M$, N , U , k , *Some* D))

using $1(1)$ **unfolding** *cdcl_W-all-struct-inv-def* *cdcl_W-conflicting-def* **by** *fast*

then have $L \in \text{set } C$ **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 $\langle -L \in \text{set } D \rangle$ **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* $C - \{\#L\# \} + \{\#L\# \} = \text{mset } C$ **using** $\langle L \in \text{set } C \rangle$ **by** (*auto simp add*: *multiset-eq-iff*)

have *get-maximum-level* (*Propagated* L ($C' + \{\#L\# \}$) $\#$ *map convert* M) $D' = k$

using $M[\text{simplified}]$ **unfolding** *maximum-level-code-eq-get-maximum-level* $C[\text{symmetric}]$ CL

by (*metis* $D D'L$ *convert.simps(1)* *get-maximum-level-map-convert list.simps(9)*)

then have

resolve

(*map convert* (*Propagated* L $C \# M$), *mset* ' $\#$ *mset* N , *mset* ' $\#$ *mset* U , k , *Some* (*mset* D))

(*map convert* M , *mset* ' $\#$ *mset* N , *mset* ' $\#$ *mset* U , k ,

Some (((*mset* $D - \{\#-L\# \}$) $\# \cup$ (*mset* $C - \{\#L\# \}$))))

unfolding *resolve.simps*

by (*simp add*: $C D$)

moreover have

(*map convert* (*Propagated* L $C \# M$), *mset* ' $\#$ *mset* N , *mset* ' $\#$ *mset* U , k , *Some* (*mset* D))

= *toS* (*Propagated* L $C \# M$, N , U , k , *Some* D)

by (*auto simp*: *mset-map*)

```

moreover
  have distinct-mset (mset C) and distinct-mset (mset D)
    using  $\langle \text{cdcl}_W\text{-all-struct-inv } (\text{toS } (\text{Propagated } L \ C \ \# \ M, \ N, \ U, \ k, \ \text{Some } D)) \rangle$ 
    unfolding cdclW-all-struct-inv-def distinct-cdclW-state-def
    by auto
  then have (mset C - {#L#}) # $\cup$  (mset D - {#- L#}) =
    remdups-mset (mset C - {#L#} + (mset D - {#- L#}))
    by (auto simp: distinct-mset-remdups-union-mset)
  then have (map convert M, mset ‘# mset N, mset ‘# mset U, k,
Some ((mset D - {#- L#}) # $\cup$  (mset C - {#L#})))
    = toS (do-resolve-step (Propagated L C # M, N, U, k, Some D))
    using  $\langle - L \in \text{set } D \rangle M$  by (auto simp: ac-simps mset-map)
  ultimately show ?case
    by simp
qed auto

lemma do-resolve-step-no:
  do-resolve-step S = S  $\implies$  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: in-multiset-in-set[symmetric] get-maximum-level-map-convert[symmetric])

lemma rough-state-of-state-of-resolve[simp]:
  cdclW-all-struct-inv (toS S)  $\implies$  rough-state-of (state-of (do-resolve-step S)) = do-resolve-step S
apply (rule state-of-inverse)
apply (cases do-resolve-step S = S)
apply simp
by (blast dest: other resolve bj do-resolve-step cdclW-all-struct-inv-inv)

lemma do-resolve-step-trail-is-None[iff]:
  do-resolve-step S = (a, b, c, d, None)  $\longleftrightarrow$  S = (a, b, c, d, None)
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 M L, 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  $L \in \text{set } Ls \wedge \text{get-maximum-level } M \ (\text{mset } (\text{remove1 } L \ (Ls @ D))) = j \wedge \text{get-level } M \ L = k$ 
  using assms
proof (induction Ls arbitrary: D)
  case Nil
  then show ?case by simp
next
  case (Cons L' Ls) note IH = this(1) and H = this(2)

  def find  $\equiv$  (if get-level M L'  $\neq$  k  $\vee$   $\neg$  get-maximum-level M (mset D + mset Ls) < get-level M L'

```

then find-level-decomp $M \text{ } Ls \text{ } (L' \# D) \text{ } k$
 else Some $(L', \text{get-maximum-level } M \text{ } (mset \text{ } D + mset \text{ } Ls))$
have $a1: \bigwedge D. \text{find-level-decomp } M \text{ } Ls \text{ } D \text{ } k = \text{Some } (L, j) \implies$
 $L \in \text{set } Ls \wedge \text{get-maximum-level } M \text{ } (mset \text{ } Ls + mset \text{ } D - \{\#L\# \}) = j \wedge \text{get-level } M \text{ } L = k$
using IH **by** simp
have $a2: \text{find} = \text{Some } (L, j)$
using H **unfolding** find-def **by** $(\text{auto split: split-if-asm})$
{ assume $\text{Some } (L', \text{get-maximum-level } M \text{ } (mset \text{ } D + mset \text{ } Ls)) \neq \text{find}$
then have $f3: L \in \text{set } Ls$ **and** $\text{get-maximum-level } M \text{ } (mset \text{ } Ls + mset \text{ } (L' \# D) - \{\#L\# \}) = j$
using $a1 \text{ } IH \text{ } a2$ **unfolding** find-def **by** meson+
moreover then have $mset \text{ } Ls + mset \text{ } D - \{\#L\# \} + \{\#L'\# \} = \{\#L'\# \} + mset \text{ } D + (mset \text{ } Ls$
 $- \{\#L\# \})$
by $(\text{auto simp: ac-simps multiset-eq-iff Suc-leI})$
ultimately have $f4: \text{get-maximum-level } M \text{ } (mset \text{ } Ls + mset \text{ } D - \{\#L\# \} + \{\#L'\# \}) = j$
by $(\text{metis (no-types) diff-union-single-conv mem-set-multiset-eq mset.simps(2) union-commute})$
} **note** $f4 = \text{this}$
have $\{\#L'\# \} + (mset \text{ } Ls + mset \text{ } D) = mset \text{ } Ls + (mset \text{ } D + \{\#L'\# \})$
by $(\text{auto simp: ac-simps})$
then have
 $(L = L' \longrightarrow \text{get-maximum-level } M \text{ } (mset \text{ } Ls + mset \text{ } D) = j \wedge \text{get-level } M \text{ } L' = k)$ **and**
 $(L \neq L' \longrightarrow L \in \text{set } Ls \wedge \text{get-maximum-level } M \text{ } (mset \text{ } Ls + mset \text{ } D - \{\#L\# \} + \{\#L'\# \}) = j \wedge$
 $\text{get-level } M \text{ } L = k)$
using $f4 \text{ } a2 \text{ } a1[\text{of } L' \# D]$ **unfolding** find-def **by** $(\text{metis (no-types) add-diff-cancel-left'}$
 $\text{mset.simps(2) option.inject prod.inject union-commute})+$
then show $?case$ **by** simp
qed

lemma *find-level-decomp-none*:

assumes $\text{find-level-decomp } M \text{ } Ls \text{ } E \text{ } k = \text{None}$ **and** $mset \text{ } (L \# D) = mset \text{ } (Ls @ E)$
shows $\neg(L \in \text{set } Ls \wedge \text{get-maximum-level } M \text{ } (mset \text{ } D) < k \wedge k = \text{get-level } M \text{ } L)$
using assms

proof $(\text{induction } Ls \text{ arbitrary: } E \text{ } L \text{ } D)$

case Nil
then show $?case$ **by** simp

next

case $(\text{Cons } L' \text{ } Ls)$ **note** $IH = \text{this}(1)$ **and** $\text{find-none} = \text{this}(2)$ **and** $LD = \text{this}(3)$
have $mset \text{ } D + \{\#L'\# \} = mset \text{ } E + (mset \text{ } Ls + \{\#L'\# \}) \implies mset \text{ } D = mset \text{ } E + mset \text{ } Ls$
by $(\text{metis add-right-imp-eq union-assoc})$
then show $?case$
using $\text{find-none } IH[\text{of } L' \# E \text{ } L \text{ } D]$ LD **by** $(\text{auto simp add: ac-simps split: split-if-asm})$

qed

fun *bt-cut* **where**

$\text{bt-cut } i \text{ } (\text{Propagated } - \text{ } \# \text{ } Ls) = \text{bt-cut } i \text{ } Ls \mid$
 $\text{bt-cut } i \text{ } (\text{Marked } K \text{ } k \text{ } \# \text{ } Ls) = (\text{if } k = \text{Suc } i \text{ then } \text{Some } (\text{Marked } K \text{ } k \text{ } \# \text{ } Ls) \text{ else } \text{bt-cut } i \text{ } Ls) \mid$
 $\text{bt-cut } i \text{ } [] = \text{None}$

lemma *bt-cut-some-decomp*:

$\text{bt-cut } i \text{ } M = \text{Some } M' \implies \exists K \text{ } M2 \text{ } M1. M = M2 @ M' \wedge M' = \text{Marked } K \text{ } (i+1) \# M1$
by $(\text{induction } i \text{ } M \text{ rule: bt-cut.induct}) \text{ } (\text{auto split: split-if-asm})$

lemma *bt-cut-not-none*: $M = M2 @ \text{Marked } K \text{ } (\text{Suc } i) \# M' \implies \text{bt-cut } i \text{ } M \neq \text{None}$

by $(\text{induction } M2 \text{ arbitrary: } M \text{ rule: marked-lit-list-induct}) \text{ } \text{auto}$

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 (rename-tac L m xs, case-tac get-all-marked-decomposition (xs @ Marked K (Suc i) # M'))
  auto

```

lemma *bt-cut-in-get-all-marked-decomposition*:

```

   $\text{bt-cut } i \text{ } M = \text{Some } M' \implies \exists M2. (M', M2) \in \text{set } (\text{get-all-marked-decomposition } M)$ 
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, Some D) =
  (case find-level-decomp M D [] k of
    None  $\Rightarrow$  (M, N, U, k, Some D)
  | Some (L, j)  $\Rightarrow$ 
    (case bt-cut j M of
      Some (Marked - - # Ls)  $\Rightarrow$  (Propagated L D # Ls, N, D # U, j, None)
    | -  $\Rightarrow$  (M, N, U, k, Some D))
  ) |
do-backtrack-step S = S

```

lemma *get-all-marked-decomposition-map-convert*:

```

  (get-all-marked-decomposition (map convert M)) =
    map ( $\lambda(a, b). (\text{map convert } a, \text{map convert } b)$ ) (get-all-marked-decomposition M)
apply (induction M rule: marked-lit-list-induct)
apply simp
by (rename-tac L l xs, case-tac get-all-marked-decomposition xs; auto)+

```

lemma *do-backtrack-step*:

```

assumes
  db: do-backtrack-step S  $\neq$  S and
  inv: cdclW-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 = this(1) and confl = this(2)
  have E: E = Some C using S confl by auto

  obtain L j where fd: find-level-decomp M C [] k = Some (L, j)
  using db unfolding S E by (cases C) (auto split: split-if-asm option.splits)
  have L  $\in$  set C and get-maximum-level M (mset (remove1 L C)) = j and
  levL: get-level M L = k
  using find-level-decomp-some[OF fd] by auto
  obtain C' where C: mset C = mset C' + {#L#}
  using  $\langle L \in \text{set } C \rangle$  by (metis add.commute ex-mset in-multiset-in-set insert-DiffM)
  obtain M2 where M2: bt-cut j M = Some M2
  using db fd unfolding S E by (auto split: option.splits)
  obtain M1 K where M1: M2 = Marked K (Suc j) # M1
  using bt-cut-some-decomp[OF M2] by (cases M2) auto
  obtain c where c: M = c @ Marked K (Suc j) # M1
  using bt-cut-in-get-all-marked-decomposition[OF M2]
  unfolding M1 by fastforce

```



```

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  $\lambda a. \text{Suc } j \in \text{set } a$ ] have  $j \leq k$  unfolding c by auto
have max-l-j: maximum-level-code C' M = j
  using db fd M2 C unfolding S E by (auto
    split: option.splits list.splits marked-lit.splits
    dest!: find-level-decomp-some)[1]
have get-maximum-level M (mset C)  $\geq k$ 
  using  $\langle L \in \text{set } C \rangle$  get-maximum-level-ge-get-level levL by blast
moreover have get-maximum-level M (mset C)  $\leq k$ 
  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 dest: sym[of get-level - -])
ultimately have get-maximum-level M (mset C) = k by auto

obtain M2 where M2: (M2, M2)  $\in \text{set } (\text{get-all-marked-decomposition } M)$ 
  using bt-cut-in-get-all-marked-decomposition[OF M2] by metis
have H: (reduce-trail-to (map convert M1)
  (add-learned-cls (mset C' + {#L#})
    (map convert M, mset (map mset N), mset (map mset U), j, None))) =
  (map convert M1, mset (map mset N), {#mset C' + {#L#}#} + mset (map mset U), j, None)
  apply (subst state-conv[of reduce-trail-to - -])
  using M2 unfolding M1 by auto
have
  backtrack
    (map convert M, mset '# mset N, mset '# mset U, k, Some (mset C))
    (Propagated L (mset C) # map convert M1, mset '# mset N, mset '# mset U + {#mset C#},
j,
  None)
  apply (rule backtrack-rule)
    unfolding C apply simp
    using Set.imageI[of (M2, 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  $\langle \text{get-maximum-level } M (\text{mset } C) = k \rangle$  levL apply auto[1]
    using max-l-j apply simp
  apply (cases reduce-trail-to (map convert M1)
    (add-learned-cls (mset C' + {#L#})
      (map convert M, mset (map mset N), mset (map mset U), j, None)))
    using M2 M1 H by (auto simp: ac-simps mset-map)
then show ?case
  using M2 fd unfolding S E M1 by (auto simp: mset-map)
obtain M2 where (M2, M2)  $\in \text{set } (\text{get-all-marked-decomposition } M)$ 
  using bt-cut-in-get-all-marked-decomposition[OF M2] 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 M L = get-maximum-level M (D + {#L#}) and
  k: k = get-maximum-level M (D + {#L#}) and
  j: j = get-maximum-level M D and
  CE: convert C E = Some (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 = Some C and
  C: mset C = mset (L # D')
  using CE apply (cases E)
  apply simp
  by (metis ex-mset mset.simps(2) option.inject option.simps(9))
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 M L' ≤ get-maximum-level M D
  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 ($M, N, U, k, None$) =
(case find-first-unused-var N (lits-of M) of
None $\Rightarrow (M, N, U, k, None)$
| Some $L \Rightarrow (\text{Marked } L\ (\text{Suc } k) \# M, N, U, k+1, None))$ |
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 $a :: (\text{nat}, \text{nat}, \text{nat literal list}) \text{ marked-lit list and}$
 $b :: \text{nat literal list list and } c :: \text{nat literal list list and}$
 $d :: \text{nat and } e :: \text{nat literal list option}$
{
fix $a :: (\text{nat}, \text{nat}, \text{nat literal list}) \text{ marked-lit list and}$
 $b :: \text{nat literal list list and } c :: \text{nat literal list list and}$
 $d :: \text{nat and } x2 :: \text{nat literal and } m :: \text{nat literal list}$
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 $H = \text{this}$
{
fix $m :: \text{nat literal list and } x2$
have $m \in \text{set } b \implies x2 \in \text{set } m \implies x2 \notin \text{lits-of } a \implies - x2 \notin \text{lits-of } a \implies$
 $\exists aa \in \text{set } b. \neg \text{atm-of } \text{' set } aa \subseteq \text{atm-of } \text{' lits-of } a$
by (meson atm-of-in-atm-of-set-in-uminus contra-subsetD rev-image-eqI)
} note $H' = \text{this}$

assume do-decide-step $S \neq S$ **and**
 $S = (a, b, c, d, e)$ **and**
conflicting $S = None$
then show $\text{decide } (toS\ S) (toS\ (do\text{-decide-step } S))$

using $H\ H'$ **by** (*auto split: option.splits simp: decide.simps Marked-Propagated-in-iff-in-lits-of*
dest!: find-first-unused-var-Some)
qed

lemma *do-decide-step-no*:
 $do-decide-step\ S = S \implies no-step\ decide\ (toS\ S)$
by (*cases S, cases conflicting S*)
(fastforce simp: atms-of-ms-mset-unfold atm-of-eq-atm-of Marked-Propagated-in-iff-in-lits-of
split: option.splits)+

lemma *rough-state-of-state-of-do-decide-step[simp]*:
 $cdcl_W\text{-all-struct-inv}\ (toS\ S) \implies rough\text{-state-of}\ (state\text{-of}\ (do-decide-step\ S)) = do-decide-step\ S$
proof (*subst state-of-inverse, goal-cases*)
case 1
then show ?*case*
by (*cases do-decide-step S = S*)
(auto dest: do-decide-step decide other intro: cdcl_W-all-struct-inv-inv)
qed *simp*

lemma *rough-state-of-state-of-do-skip-step[simp]*:
 $cdcl_W\text{-all-struct-inv}\ (toS\ S) \implies rough\text{-state-of}\ (state\text{-of}\ (do-skip-step\ S)) = do-skip-step\ S$
apply (*subst state-of-inverse, cases do-skip-step S = S*)
apply *simp*
by (*blast dest: other skip bj do-skip-step cdcl_W-all-struct-inv-inv*)+

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**
 $Con\ xs = state\text{-of}\ (if\ cdcl_W\text{-all-struct-inv}\ (toS\ (fst\ xs,\ snd\ xs))\ then\ xs$
 $else\ ([], [], [], 0, None))$

lemma [*code abstype*]:
 $Con\ (rough\text{-state-of}\ S) = S$
using *rough-state-of[of S]* **unfolding** *Con-def* **by** *simp*

definition *do-cp-step'* **where**
 $do-cp-step'\ S = state\text{-of}\ (do-cp-step\ (rough\text{-state-of}\ S))$

typedef *cdcl_W-state-inv-from-init-state* = $\{S::cdcl_W\text{-state-inv-st}.\ cdcl_W\text{-all-struct-inv}\ (toS\ S)$
 $\wedge\ cdcl_W\text{-stgy}^{**}\ (S0\text{-cdcl}_W\ (clss\ (toS\ S)))\ (toS\ S)\}$
morphisms *rough-state-from-init-state-of state-from-init-state-of*
proof
show $([], [], [], 0, None) \in \{S.\ cdcl_W\text{-all-struct-inv}\ (toS\ S)$
 $\wedge\ cdcl_W\text{-stgy}^{**}\ (S0\text{-cdcl}_W\ (clss\ (toS\ S)))\ (toS\ S)\}$
by (*auto simp add: cdcl_W-all-struct-inv-def*)
qed

instantiation *cdcl_W-state-inv-from-init-state* :: *equal*
begin

definition *equal-cdcl_W-state-inv-from-init-state* :: *cdcl_W-state-inv-from-init-state* \Rightarrow
 $cdcl_W\text{-state-inv-from-init-state} \Rightarrow bool$ **where**
 $equal\text{-cdcl}_W\text{-state-inv-from-init-state}\ S\ S' \longleftrightarrow$

(*rough-state-from-init-state-of* $S = \text{rough-state-from-init-state-of } S'$)

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 $S = \text{state-from-init-state-of } (\text{if } \text{cdcl}_W\text{-all-struct-inv } (\text{toS } (\text{fst } S, \text{snd } S))$
 $\wedge \text{cdcl}_W\text{-stgy}^{**} (S0\text{-cdcl}_W (\text{clss } (\text{toS } S))) (\text{toS } S) \text{ then } S \text{ else } ([], [], [], 0, \text{None}))$

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 $S = \text{state-of } (\text{rough-state-from-init-state-of } S)$

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* $S' = \text{do-cp-step}' S$ *in*
if $S = S'$ *then* S *else* *do-full1-cp-step* S')

by *auto*

termination

proof (*relation* $\{(T', T). (\text{rough-state-of } T', \text{rough-state-of } T) \in \{(S', S).$

$(\text{toS } S', \text{toS } S) \in \{(S', S). \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-cp } S S'\}\}$, *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 (*2* $S' S$)

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* $\lambda S. \text{do-cp-step}(\text{rough-state-of } (\text{do-full1-cp-step } S))$

= (*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*:

$c \in \text{set } (\text{clss } (\text{rough-state-of } S) @ \text{learned-clss } (\text{rough-state-of } S)) \implies \text{distinct } c$

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
proof (rule conjI, induction S rule: do-full1-cp-step.induct)
case (1 S)
then have f1:
  cdclW-cp** (toS (do-cp-step (rough-state-of S))) (
    toS (rough-state-of (do-full1-cp-step (state-of (do-cp-step (rough-state-of S))))))
  ∨ state-of (do-cp-step (rough-state-of S)) = S
  using do-cp-step'-def rough-state-of-state-of-do-cp-step by fastforce
have f2: ∧c. (if c = state-of (do-cp-step (rough-state-of c))
  then c else do-full1-cp-step (state-of (do-cp-step (rough-state-of c))))
  = do-full1-cp-step c
  by (metis (full-types) do-cp-step'-def do-full1-cp-step.simps)
have f3: ¬ cdclW-cp (toS (rough-state-of S)) (toS (do-cp-step (rough-state-of S)))
  ∨ state-of (do-cp-step (rough-state-of S)) = S
  ∨ cdclW-cp++ (toS (rough-state-of S))
    (toS (rough-state-of (do-full1-cp-step (state-of (do-cp-step (rough-state-of S))))))
  using f1 by (meson rtranclp-into-tranclp2)
{ assume do-full1-cp-step S ≠ S
  then have do-cp-step (rough-state-of S) = rough-state-of S
    → cdclW-cp** (toS (rough-state-of S)) (toS (rough-state-of (do-full1-cp-step S)))
    ∨ do-cp-step (rough-state-of S) ≠ rough-state-of S
    ∧ state-of (do-cp-step (rough-state-of S)) ≠ S
    using f2 f1 by (metis (no-types))
  then have do-cp-step (rough-state-of S) ≠ rough-state-of S
    ∧ state-of (do-cp-step (rough-state-of S)) ≠ S
    ∨ cdclW-cp** (toS (rough-state-of S)) (toS (rough-state-of (do-full1-cp-step S)))
    by (metis rough-state-of-state-of-do-cp-step)
  then have cdclW-cp** (toS (rough-state-of S)) (toS (rough-state-of (do-full1-cp-step S)))
    using f3 f2 by (metis (no-types) cp-step-is-cdclW-cp tranclp-into-rtranclp) }
then show ?case
  by fastforce
next
show no-step cdclW-cp (toS (rough-state-of (do-full1-cp-step S)))
  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
qed

```

lemma [code abstract]:
 $\text{rough-state-of (do-cp-step' } S) = \text{do-cp-step (rough-state-of } S)$
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 ≠ S
    then T
    else
      (let U = do-resolve-step T in
        if U ≠ T
        then U else
          (let V = do-backtrack-step U in
            if V ≠ 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** (*auto intro: cdcl_W-all-struct-inv-inv*
cdcl_W-all-struct-inv-rough-state other state-of-inverse)

definition *do-cdcl_W-stgy-step* **where**
do-cdcl_W-stgy-step S =
(let T = do-full1-cp-step S in
if T $\neq S$
then T
else
(let U = (do-other-step' T) in
(do-full1-cp-step U)))

definition *do-cdcl_W-stgy-step'* **where**
do-cdcl_W-stgy-step' S = *state-from-init-state-of (rough-state-of (do-cdcl_W-stgy-step (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 $S \neq do_cp_step'\ S$
 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-confl*
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-confl*
do-full1-cp-step-fix-point-of-do-full1-cp-step)
then have *no-step cdcl_W-cp (toS (rough-state-of S))*
 by (*simp add: cdcl_W-cp.simps*)
moreover have *full cdcl_W-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-cdcl_W-stgy-step-def*
 by (*auto intro!: cdcl_W-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) \neq None \longleftrightarrow conflicting S \neq None
by (*cases S*) *auto*

lemma *trail-toS-neq-imp-trail-neq*:
trail (toS S) \neq trail (toS S') \implies trail S \neq 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:  $\bigwedge M K M1 c. M = c @ K \# M1 \implies \text{Suc}(\text{length } M1) \leq \text{length } M$ 
    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#}))
    (reduce-trail-to M1
      (add-learned-cls (D + {#L#}))
      (update-backtrack-lvl (get-maximum-level (trail (toS S)) D)
        (update-conflicting None (toS S))))))
  =
  (Propagated L (D + {#L#})# M1, mset (map mset (cls S)),
    {#D + {#L#}#} + mset (map mset (learned-clss S)),
    get-maximum-level (trail (toS S)) D, None)
  apply (subst state-conv[of cons-trail - -])
  using decomp undef by (cases S) auto
  then show ?case
    apply (cases do-other-step S)
    apply (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 simp: Let-def)
    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 (*rename-tac S, 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*:

conflicting (rough-state-of S) \neq None \implies do-cp-step' S = S
unfolding *do-cp-step'-def do-cp-step-def* **by** *simp*

lemma *do-full1-cp-step-conflicting*:

conflicting (rough-state-of S) \neq None \implies do-full1-cp-step S = S
unfolding *do-cp-step'-def do-cp-step-def*
apply (*induction rule: do-full1-cp-step-induct*)
by (*rename-tac S, case-tac S \neq do-cp-step' S*)
(auto simp add: do-full1-cp-step.simps do-cp-step-conflicting)

lemma *do-decide-step-not-conflicting-one-more-decide*:

assumes
conflicting S = None and
do-decide-step S \neq S
shows *Suc (length (filter is-marked (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 None and*
do-decide-step S \neq S
shows *length (filter is-marked (trail S)) < length (filter is-marked (trail (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 None and
conflicting (rough-state-of (do-other-step' S)) = None and
do-other-step' S \neq S
shows *length (filter is-marked (trail (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 = this(1) and inv = this(2)*

```

obtain  $M\ N\ U\ k\ E$  where  $y: y = (M, N, U, k, \text{Some } E)$ 
  using  $\text{assms}(1)\ S\ \text{inv}$  by ( $\text{cases } y, \text{cases conflicting } y$ )  $\text{auto}$ 
have  $M: \text{rough-state-of } (\text{state-of } (M, N, U, k, \text{Some } E)) = (M, N, U, k, \text{Some } E)$ 
  using  $\text{inv } y$  by ( $\text{auto simp add: state-of-inverse}$ )
have  $\text{bt}: \text{do-other-step}' S = \text{state-of } (\text{do-backtrack-step } (\text{rough-state-of } S))$ 
proof ( $\text{cases rough-state-of } S\ \text{rule: do-decide-step.cases}$ )
  case 1
  then show  $?thesis$ 
    using  $\text{assms}(1,2)$  by  $\text{auto}[]$ 
next
  case ( $2\ v\ vb\ vd\ vf\ vh$ )
  have  $f3: \bigwedge c. (\text{if } \text{do-skip-step } (\text{rough-state-of } c) \neq \text{rough-state-of } c$ 
    then  $\text{do-skip-step } (\text{rough-state-of } c)$ 
    else if  $\text{do-resolve-step } (\text{do-skip-step } (\text{rough-state-of } c)) \neq \text{do-skip-step } (\text{rough-state-of } c)$ 
      then  $\text{do-resolve-step } (\text{do-skip-step } (\text{rough-state-of } c))$ 
      else if  $\text{do-backtrack-step } (\text{do-resolve-step } (\text{do-skip-step } (\text{rough-state-of } c)))$ 
         $\neq \text{do-resolve-step } (\text{do-skip-step } (\text{rough-state-of } c))$ 
        then  $\text{do-backtrack-step } (\text{do-resolve-step } (\text{do-skip-step } (\text{rough-state-of } c)))$ 
        else  $\text{do-decide-step } (\text{do-backtrack-step } (\text{do-resolve-step } (\text{do-skip-step } (\text{rough-state-of } c))))$ 
         $= \text{rough-state-of } (\text{do-other-step}' c)$ 
      by ( $\text{simp add: rough-state-of-do-other-step}'$ )
    have ( $\text{trail } (\text{rough-state-of } (\text{do-other-step}' S)), \text{clss } (\text{rough-state-of } (\text{do-other-step}' S)),$ 
       $\text{learned-clss } (\text{rough-state-of } (\text{do-other-step}' S)),$ 
       $\text{backtrack-lvl } (\text{rough-state-of } (\text{do-other-step}' S)), \text{None}$ )
       $= \text{rough-state-of } (\text{do-other-step}' S)$ 
    using  $\text{assms}(2)$  by ( $\text{metis (no-types) state-conv}$ )
    then show  $?thesis$ 
      using  $f3\ 2$  by ( $\text{metis (no-types) do-decide-step.simps}(2)\ \text{do-resolve-step-trail-is-None}$ 
         $\text{do-skip-step-trail-is-None rough-state-of-inverse}$ )
  qed
show  $?case$ 
  using  $\text{assms}(2)\ S\ \text{unfolding } \text{bt } y\ \text{inv}$ 
  apply  $\text{simp}$ 
  by ( $\text{auto simp add: } M\ \text{bt-cut-not-none}$ 
     $\text{split: option.splits}$ 
     $\text{dest!: bt-cut-some-decomp}$ )
qed

lemma  $\text{do-other-step-not-conflicting-one-more-decide:}$ 
  assumes  $\text{conflicting } (\text{rough-state-of } S) = \text{None}$  and
   $\text{do-other-step}' S \neq S$ 
  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 ( $\text{cases } S, \text{goal-cases}$ )
  case ( $1\ y$ ) note  $S = \text{this}(1)$  and  $\text{inv} = \text{this}(2)$ 
  obtain  $M\ N\ U\ k$  where  $y: y = (M, N, U, k, \text{None})$  using  $\text{assms}(1)\ S\ \text{inv}$  by ( $\text{cases } y$ )  $\text{auto}$ 
  have  $M: \text{rough-state-of } (\text{state-of } (M, N, U, k, \text{None})) = (M, N, U, k, \text{None})$ 
    using  $\text{inv } y$  by ( $\text{auto simp add: state-of-inverse}$ )
  have  $\text{state-of } (\text{do-decide-step } (M, N, U, k, \text{None})) \neq \text{state-of } (M, N, U, k, \text{None})$ 
    using  $\text{assms}(2)$  unfolding  $\text{do-other-step}'\text{-def } y\ \text{inv } S$  by ( $\text{auto simp add: } M$ )
  then have  $f4: \text{do-skip-step } (\text{rough-state-of } S) = \text{rough-state-of } S$ 
    unfolding  $S\ M\ y$  by ( $\text{metis (full-types) do-skip-step.simps}(4)$ )
  have  $f5: \text{do-resolve-step } (\text{rough-state-of } S) = \text{rough-state-of } S$ 
    unfolding  $S\ M\ y$  by ( $\text{metis (no-types) do-resolve-step.simps}(4)$ )

```

have $f6$: $\text{do-backtrack-step (rough-state-of } S) = \text{rough-state-of } S$
unfolding $S \ M \ y$ **by** (*metis (no-types) do-backtrack-step.simps(2)*)
have $\text{do-other-step (rough-state-of } S) \neq \text{rough-state-of } S$
using *assms(2)* **unfolding** $S \ M \ y$ $\text{do-other-step'-def}$ **by** (*metis (no-types)*)
then show *?case*
using $f6 \ f5 \ f4$ **by** (*simp add: assms(1) do-decide-step-not-conflicting-one-more-decide*
 $\text{do-other-step'-def}$)
qed

lemma $\text{rough-state-of-state-of-do-skip-step-rough-state-of}[simp]$:
 $\text{rough-state-of (state-of (do-skip-step (rough-state-of } S))) = \text{do-skip-step (rough-state-of } S)$
by (*smt do-other-step.simps rough-state-of-inverse rough-state-of-state-of-do-other-step*)

lemma $\text{conflicting-do-resolve-step-iff}[iff]$:
 $\text{conflicting (do-resolve-step } S) = \text{None} \longleftrightarrow \text{conflicting } S = \text{None}$
by (*cases S rule: do-resolve-step.cases*)
(auto simp add: Let-def split: option.splits)

lemma $\text{conflicting-do-skip-step-iff}[iff]$:
 $\text{conflicting (do-skip-step } S) = \text{None} \longleftrightarrow \text{conflicting } S = \text{None}$
by (*cases S rule: do-skip-step.cases*)
(auto simp add: Let-def split: option.splits)

lemma $\text{conflicting-do-decide-step-iff}[iff]$:
 $\text{conflicting (do-decide-step } S) = \text{None} \longleftrightarrow \text{conflicting } S = \text{None}$
by (*cases S rule: do-decide-step.cases*)
(auto simp add: Let-def split: option.splits)

lemma $\text{conflicting-do-backtrack-step-imp}[simp]$:
 $\text{do-backtrack-step } S \neq S \implies \text{conflicting (do-backtrack-step } S) = \text{None}$
by (*cases S rule: do-backtrack-step.cases*)
(auto simp add: Let-def split: list.splits option.splits marked-lit.splits)

lemma $\text{do-skip-step-eq-iff-trail-eq}$:
 $\text{do-skip-step } S = S \longleftrightarrow \text{trail (do-skip-step } S) = \text{trail } S$
by (*cases S rule: do-skip-step.cases*) *auto*

lemma $\text{do-decide-step-eq-iff-trail-eq}$:
 $\text{do-decide-step } S = S \longleftrightarrow \text{trail (do-decide-step } S) = \text{trail } S$
by (*cases S rule: do-decide-step.cases*) *(auto split: option.split)*

lemma $\text{do-backtrack-step-eq-iff-trail-eq}$:
 $\text{do-backtrack-step } S = S \longleftrightarrow \text{trail (do-backtrack-step } S) = \text{trail } S$
by (*cases S rule: do-backtrack-step.cases*)
(auto split: option.split list.splits marked-lit.splits
 $\text{dest!:: bt-cut-in-get-all-marked-decomposition})$

lemma $\text{do-resolve-step-eq-iff-trail-eq}$:
 $\text{do-resolve-step } S = S \longleftrightarrow \text{trail (do-resolve-step } S) = \text{trail } S$
by (*cases S rule: do-resolve-step.cases*) *auto*

lemma $\text{do-other-step-eq-iff-trail-eq}$:
 $\text{trail (do-other-step } S) = \text{trail } S \longleftrightarrow \text{do-other-step } S = S$
by (*auto simp add: Let-def do-skip-step-eq-iff-trail-eq[symmetric]*
 $\text{do-decide-step-eq-iff-trail-eq[symmetric] do-backtrack-step-eq-iff-trail-eq[symmetric]}$)

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 *None*

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*

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* $\lambda S. \text{trail } (\text{rough-state-of } S)$]

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*) = *None* **and** *neq*: *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* - *neq*]

do-other-step-not-conflicting-one-more-decide-bt[*of* *S*, *OF* - *confl neq*]

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 cdcl_W-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 *cdcl_W-cp-is-rtrancpl-cdcl_W*: $cdcl_W\text{-}cp\ S\ T \implies cdcl_W^{**}\ S\ T$
 apply (induction rule: cdcl_W-cp.induct)
 using conflict apply blast
 using propagate by blast

lemma *rtrancpl-cdcl_W-cp-is-rtrancpl-cdcl_W*: $cdcl_W\text{-}cp^{**}\ S\ T \implies cdcl_W^{**}\ S\ T$
 apply (induction rule: rtrancpl-induct)
 apply simp
 by (fastforce dest!: cdcl_W-cp-is-rtrancpl-cdcl_W)

lemma *cdcl_W-stgy-is-rtrancpl-cdcl_W*:
 $cdcl_W\text{-}stgy\ S\ T \implies cdcl_W^{**}\ S\ T$
 apply (induction rule: cdcl_W-stgy.induct)
 using cdcl_W-stgy.conflict' rtrancpl-cdcl_W-stgy-rtrancpl-cdcl_W apply blast
 unfolding full-def by (fastforce dest!: other rtrancpl-cdcl_W-cp-is-rtrancpl-cdcl_W)

lemma *cdcl_W-stgy-init-clss*: $cdcl_W\text{-}stgy\ S\ T \implies cdcl_W\text{-}M\text{-level}\text{-}inv\ S \implies clss\ S = clss\ T$
 using rtrancpl-cdcl_W-init-clss cdcl_W-stgy-is-rtrancpl-cdcl_W by fast

lemma *clauses-toS-rough-state-of-do-cdcl_W-stgy-step*[simp]:
 $clss\ (toS\ (rough\text{-}state\text{-}of\ (do\text{-}cdcl_W\text{-}stgy\text{-}step\ (state\text{-}of\ (rough\text{-}state\text{-}from\text{-}init\text{-}state\text{-}of\ S))))$
 = $clss\ (toS\ (rough\text{-}state\text{-}from\text{-}init\text{-}state\text{-}of\ S))\ (\text{is} - = clss\ (toS\ ?S))$
 apply (cases do-cdcl_W-stgy-step (state-of ?S) = state-of ?S)
 apply simp
 by (smt cdcl_W-all-struct-inv-def cdcl_W-all-struct-inv-rough-state cdcl_W-stgy-no-more-init-clss
 do-cdcl_W-stgy-step toS-rough-state-of-state-of-rough-state-from-init-state-of)

lemma *rough-state-from-init-state-of-do-cdcl_W-stgy-step'*[code abstract]:
 rough-state-from-init-state-of (do-cdcl_W-stgy-step' S) =
 rough-state-of (do-cdcl_W-stgy-step (id-of-I-to S))

proof –
 let ?S = (rough-state-from-init-state-of S)
 have cdcl_W-stgy^{**} (S0-cdcl_W (clss (toS (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
  moreover have cdclW-stgy**
    (toS (rough-state-from-init-state-of S))
    (toS (rough-state-of (do-cdclW-stgy-step
      (state-of (rough-state-from-init-state-of S))))))
  using do-cdclW-stgy-step[of state-of ?S]
  by (cases do-cdclW-stgy-step (state-of ?S) = state-of ?S) auto
  ultimately show ?thesis
  unfolding do-cdclW-stgy-step'-def id-of-I-to-def
  by (auto intro!: state-from-init-state-of-inverse)
qed

```

All rules together function *do-all-cdcl_W-stgy* where

```

do-all-cdclW-stgy S =
  (let T = do-cdclW-stgy-step' S in
  if T = S then S else do-all-cdclW-stgy T)
by fast+
termination
proof (relation {(T, S).
  (cdclW-measure (toS (rough-state-from-init-state-of T)),
  cdclW-measure (toS (rough-state-from-init-state-of S)))
  ∈ lern {(a, b). a < b} 3}, goal-cases)
case 1
show ?case by (rule wf-if-measure-f) (auto intro!: wf-lern wf-less)
next
case (2 S T) note T = this(1) and ST = this(2)
let ?S = rough-state-from-init-state-of S
have S: cdclW-stgy** (S0-cdclW (clss (toS ?S))) (toS ?S)
  using rough-state-from-init-state-of[of S] by auto
moreover have cdclW-stgy (toS (rough-state-from-init-state-of S))
  (toS (rough-state-from-init-state-of T))
proof -
  have ∧c. rough-state-of (state-of (rough-state-from-init-state-of c)) =
    rough-state-from-init-state-of c
  using rough-state-from-init-state-of by force
  then have do-cdclW-stgy-step (state-of (rough-state-from-init-state-of S))
    ≠ state-of (rough-state-from-init-state-of S)
  using ST T by (metis (no-types) id-of-I-to-def rough-state-from-init-state-of-inject
    rough-state-from-init-state-of-do-cdclW-stgy-step')
  then show ?thesis
  using do-cdclW-stgy-step id-of-I-to-def rough-state-from-init-state-of-do-cdclW-stgy-step' T
  by fastforce
qed
moreover
have cdclW-all-struct-inv (toS (rough-state-from-init-state-of S))
  using rough-state-from-init-state-of[of S] by auto
then have cdclW-all-struct-inv (S0-cdclW (clss (toS (rough-state-from-init-state-of S))))
  by (cases rough-state-from-init-state-of S)
  (auto simp add: cdclW-all-struct-inv-def distinct-cdclW-state-def)
ultimately show ?case
  by (auto intro!: cdclW-stgy-step-decreasing[of - - S0-cdclW (clss (toS ?S))]
    simp del: cdclW-measure.simps)
qed

```

```

thm do-all-cdclW-stgy.induct
lemma do-all-cdclW-stgy.induct:
  ( $\bigwedge S. (do-cdcl_W-stgy-step' S \neq S \implies P (do-cdcl_W-stgy-step' S)) \implies P S) \implies P a0$ )
using do-all-cdclW-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 (rename-tac S, case-tac do-cdclW-stgy-step' S \neq S)
proof –
  fix Sa :: cdclW-state-inv-from-init-state
assume a1:  $\neg do-cdcl_W-stgy-step' Sa \neq Sa$ 
  { fix pp
    have (if True then Sa else do-all-cdclW-stgy Sa) = do-all-cdclW-stgy Sa
      using a1 by auto
    then have  $\neg cdcl_W-stgy (toS (rough-state-from-init-state-of (do-all-cdcl_W-stgy Sa)))$  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 \neq Sa
   $\implies no-step cdcl_W-stgy (toS (rough-state-from-init-state-of$ 
     $(do-all-cdcl_W-stgy (do-cdcl_W-stgy-step' Sa))))$ 
assume a2: do-cdclW-stgy-step' Sa \neq 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)))
proof (induction S rule: do-all-cdclW-stgy.induct)
case (1 S) note IH = this(1)
show ?case
  proof (cases do-cdclW-stgy-step' S = S)
    case True
    then show ?thesis by simp
  next
    case False
    have f2: do-cdclW-stgy-step (id-of-I-to S) = id-of-I-to S  $\longrightarrow$ 
      rough-state-from-init-state-of (do-cdclW-stgy-step' S)
      = rough-state-of (state-of (rough-state-from-init-state-of S))
      using id-of-I-to-def rough-state-from-init-state-of-do-cdclW-stgy-step' by presburger
    have f3: do-all-cdclW-stgy S = do-all-cdclW-stgy (do-cdclW-stgy-step' S)
      by (metis (full-types) do-all-cdclW-stgy.simps)
    have cdclW-stgy (toS (rough-state-from-init-state-of S))
      (toS (rough-state-from-init-state-of (do-cdclW-stgy-step' S)))
      = cdclW-stgy (toS (rough-state-of (id-of-I-to S)))
      (toS (rough-state-of (do-cdclW-stgy-step (id-of-I-to S))))
      using 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 by presburger

```



```

    then show ?thesis
    using f3 f2 IH do-cdclW-stgy-step by fastforce
qed
qed

```

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, None))) = S and
  S: (M', N', U', k, E) = toS S
shows (E ≠ Some {#} ∧ satisfiable (set (map mset N)))
  ∨ (E = Some {#} ∧ unsatisfiable (set (map mset N)))
proof –
  let ?N = map remdups N
  have inv: cdclW-all-struct-inv (toS ([], map remdups N, [], 0, None))
  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, None))
    = ([], map remdups N, [], 0, None) by simp
  have 1: full cdclW-stgy (toS ([], ?N, [], 0, None)) (toS S)
  unfolding full-def apply rule
  using do-all-cdclW-stgy-is-rtranclp-cdclW-stgy[of
    state-from-init-state-of ([], map remdups N, [], 0, None)] 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 clss (toS ([], ?N, [], 0, None)) = clss (toS S)
  apply (rule rtranclp-cdclW-init-clss)
  using 1 unfolding full-def by (auto simp add: rtranclp-cdclW-stgy-rtranclp-cdclW)
  then have N': mset (map mset ?N) = N'
  using S[symmetric] by auto
  have (E ≠ Some {#} ∧ satisfiable (set (map mset ?N)))
  ∨ (E = Some {#} ∧ 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-cls)
  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. The only difference between the generated code and the one used here is the export of the constructor `ConI`.

```

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
begin

```

lemma *backtrack-levE*:

```

  backtrack S S'  $\implies$  cdclW-M-level-inv S  $\implies$ 
  ( $\bigwedge$  D L K M1 M2.
    (Marked K (Suc (get-maximum-level (trail S) D)) # M1, M2)
     $\in$  set (get-all-marked-decomposition (trail S))  $\implies$ 
    get-level (trail S) L = get-maximum-level (trail S) (D + {#L#})  $\implies$ 
    undefined-lit M1 L  $\implies$ 
    S'  $\sim$  cons-trail (Propagated L (D + {#L#}))
    (reduce-trail-to M1 (add-learned-cls (D + {#L#}))
      (update-backtrack-lvl (get-maximum-level (trail S) D) (update-conflicting None S)))  $\implies$ 
    backtrack-lvl S = get-maximum-level (trail S) (D + {#L#})  $\implies$ 
    conflicting S = Some (D + {#L#})  $\implies$  P)  $\implies$ 
  P
  using assms by (induction rule: backtrack-induction-lev2) metis

```

lemma *backtrack-no-cdcl_W-bj*:

```

  assumes cdcl: cdclW-bj T U and inv: cdclW-M-level-inv V
  shows  $\neg$ backtrack V T
  using cdcl inv
  apply (induction rule: cdclW-bj.induct)
  apply (elim skipE, force elim!: backtrack-levE[OF - inv] simp: cdclW-M-level-inv-def)
  apply (elim resolveE, force elim!: backtrack-levE[OF - inv] simp: cdclW-M-level-inv-def)
  apply standard
  apply (elim backtrack-levE[OF - inv], elim backtrackE)
  apply (force simp del: state-simp simp add: state-eq-conflicting cdclW-M-level-inv-decomp)
  done

```

abbreviation *skip-or-resolve* :: 'st \Rightarrow 'st \Rightarrow bool **where**

skip-or-resolve $\equiv (\lambda S T. \text{skip } S T \vee \text{resolve } S T)$

lemma *rtranchp-cdcl_W-bj-skip-or-resolve-backtrack*:

```

  assumes cdclW-bj** S U and inv: cdclW-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) cdclW-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 cdclW] other by blast
  then have skip-or-resolve** S U
    using bj IH inv backtrack-no-cdclW-bj rtrancpl-cdclW-consistent-inv[OF - inv] by meson
  then show ?thesis
    using bj by (metis (no-types, lifting) cdclW-bj.cases rtrancpl.simps)
next
  case SU
  then show ?thesis
    using bj by (metis (no-types, lifting) cdclW-bj.cases rtrancpl.simps)
qed
qed

```

lemma rtrancpl-skip-or-resolve-rtrancpl-cdcl_W:
 skip-or-resolve^{**} S T \implies cdcl_W^{**} S T
by (induction rule: rtrancpl-induct) (auto dest!: cdcl_W-bj.intros cdcl_W.intros cdcl_W-o.intros)

definition backjump-l-cond :: 'v clause \Rightarrow 'v clause \Rightarrow 'v literal \Rightarrow 'st \Rightarrow bool **where**
 backjump-l-cond $\equiv \lambda C C' L' S. \text{True}$

definition inv_{NOT} :: 'st \Rightarrow bool **where**
 inv_{NOT} $\equiv \lambda S. \text{no-dup (trail } S)$

declare inv_{NOT}-def[simp]
end

fun convert-marked-lit-from-W **where**
 convert-marked-lit-from-W (Propagated L -) = Propagated L () |
 convert-marked-lit-from-W (Marked L -) = Marked L ()

abbreviation convert-trail-from-W ::
 ('v, 'lvl, 'a) marked-lit list
 \Rightarrow ('v, unit, unit) marked-lit list **where**
 convert-trail-from-W $\equiv \text{map convert-marked-lit-from-W}$

lemma lits-of-convert-trail-from-W[simp]:
 lits-of (convert-trail-from-W M) = lits-of M
by (induction rule: marked-lit-list-induct) simp-all

lemma lit-of-convert-trail-from-W[simp]:
 lit-of (convert-marked-lit-from-W L) = lit-of L
by (cases L) auto

lemma no-dup-convert-from-W[simp]:
 no-dup (convert-trail-from-W M) \longleftrightarrow no-dup M
by (auto simp: comp-def)

lemma convert-trail-from-W-true-annots[simp]:

convert-trail-from-W $M \models_{as} C \longleftrightarrow M \models_{as} C$
by (*auto simp: true-annots-true-cls*)

lemma *defined-lit-convert-trail-from-W*[*simp*]:
defined-lit (*convert-trail-from-W* S) $L \longleftrightarrow$ *defined-lit* S L
by (*auto simp: defined-lit-map image-comp*)

The values 0 and $\{\#\}$ are dummy values.

fun *convert-marked-lit-from-NOT*
 $:: ('a, 'e, 'b) \text{ marked-lit} \Rightarrow ('a, \text{nat}, 'a \text{ literal multiset}) \text{ marked-lit}$ **where**
convert-marked-lit-from-NOT (*Propagated* L $-$) = *Propagated* L $\{\#\}$ |
convert-marked-lit-from-NOT (*Marked* L $-$) = *Marked* L 0

abbreviation *convert-trail-from-NOT* **where**
convert-trail-from-NOT \equiv *map convert-marked-lit-from-NOT*

lemma *undefined-lit-convert-trail-from-NOT*[*simp*]:
undefined-lit (*convert-trail-from-NOT* F) $L \longleftrightarrow$ *undefined-lit* F L
by (*induction F rule: marked-lit-list-induct*) (*auto simp: defined-lit-map*)

lemma *lits-of-convert-trail-from-NOT*:
lits-of (*convert-trail-from-NOT* F) = *lits-of* F
by (*induction F rule: marked-lit-list-induct*) *auto*

lemma *convert-trail-from-W-from-NOT*[*simp*]:
convert-trail-from-W (*convert-trail-from-NOT* M) = M
by (*induction rule: marked-lit-list-induct*) *auto*

lemma *convert-trail-from-W-convert-lit-from-NOT*[*simp*]:
convert-marked-lit-from-W (*convert-marked-lit-from-NOT* L) = L
by (*cases L*) *auto*

abbreviation *trail_{NOT}* **where**
trail_{NOT} $S \equiv$ *convert-trail-from-W* (*fst* S)

lemma *undefined-lit-convert-trail-from-W*[*iff*]:
undefined-lit (*convert-trail-from-W* M) $L \longleftrightarrow$ *undefined-lit* M L
by (*auto simp: defined-lit-map image-comp*)

lemma *lit-of-convert-marked-lit-from-NOT*[*iff*]:
lit-of (*convert-marked-lit-from-NOT* L) = *lit-of* L
by (*cases L*) *auto*

sublocale *state_W* \subseteq *dpll-state*
 $\lambda S.$ *convert-trail-from-W* (*trail* S)
clauses
 λL $S.$ *cons-trail* (*convert-marked-lit-from-NOT* L) S
 $\lambda S.$ *tl-trail* S
 λC $S.$ *add-learned-cls* C S
 λC $S.$ *remove-cls* C S
by *unfold-locales* (*auto simp: map-tl o-def*)

context *state_W*
begin
declare *state-simp_{NOT}*[*simp del*]

end

sublocale $cdcl_W \subseteq cdcl_{NOT-merge-bj-learn-ops}$

$\lambda S. \text{convert-trail-from-}W \text{ (trail } S)$

clauses

$\lambda L S. \text{cons-trail (convert-marked-lit-from-NOT } L) S$

$\lambda S. \text{tl-trail } S$

$\lambda C S. \text{add-learned-cls } C S$

$\lambda C S. \text{remove-cls } C S$

$\lambda - -. \text{True}$

$\lambda - S. \text{conflicting } S = \text{None}$

$\lambda C C' L' S. \text{backjump-l-cond } C C' L' S \wedge \text{distinct-mset } (C' + \{\#L'\# \}) \wedge \neg \text{tautology } (C' + \{\#L'\# \})$

by *unfold-locales*

sublocale $cdcl_W \subseteq cdcl_{NOT-merge-bj-learn-proxy}$

$\lambda S. \text{convert-trail-from-}W \text{ (trail } S)$

clauses

$\lambda L S. \text{cons-trail (convert-marked-lit-from-NOT } L) S$

$\lambda S. \text{tl-trail } S$

$\lambda C S. \text{add-learned-cls } C S$

$\lambda C S. \text{remove-cls } C S$

$\lambda - -. \text{True}$

$\lambda - S. \text{conflicting } S = \text{None backjump-l-cond inv}_{NOT}$

proof (*unfold-locales, goal-cases*)

case 2

then show ?case **using** $cdcl_{NOT-merged-bj-learn-no-dup-inv}$ **by** (*auto simp: comp-def*)

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 (*metis count-mset-set(3) 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 $\langle \text{inv}_{NOT} S \rangle \langle \text{convert-trail-from-}W \text{ (trail } S) = F' @ \text{Marked } K () \# F \rangle$

unfolding $\text{inv}_{NOT}\text{-def}$

by (*smt comp-apply distinct.simps(2) distinct-append list.simps(9) map-append*
 $\text{no-dup-convert-from-}W$)

then have *consistent-interp* (*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** (*metis CNot-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 $f2: \text{no-dup (convert-trail-from-}W \text{ (trail } S))$

using $\langle \text{inv}_{NOT} S \rangle$ **unfolding** $\text{inv}_{NOT}\text{-def}$ **by** (*simp add: o-def*)

have $f3: \text{atm-of } L \in \text{atms-of-msu (clauses } S)$

```

    ∪ atm-of ' lits-of (convert-trail-from-W (trail S))
    using (convert-trail-from-W (trail S) = F' @ Marked K () # F)
    ⟨atm-of L ∈ atms-of-msu (clauses S) ∪ atm-of ' lits-of (F' @ Marked K () # F)⟩ by auto
  have f4: clauses S ⊢pm remdups-mset C' + {#L#}
    by (metis (no-types) ⟨L ∉ # C'⟩ ⟨clauses S ⊢pm C' + {#L#}⟩ remdups-mset-singleton-sum(2)
        true-clss-cls-remdups-mset union-commute)
  have F ⊢as CNot (remdups-mset C')
    by (simp add: ⟨F ⊢as CNot C'⟩)
  then show ?thesis
    using f4 f3 f2 ⟨¬ tautology (remdups-mset C' + {#L#})⟩
    backjump-l.intros[OF - f2] calculation(2-5,9)
    state-eqNOT-ref unfolding backjump-l-cond-def by blast
qed
qed

```

```

sublocale cdclW ⊆ cdclNOT-merge-bj-learn-proxy2
  λS. convert-trail-from-W (trail S)
  clauses
  λL S. cons-trail (convert-marked-lit-from-NOT L) S
  λS. tl-trail S
  λC S. add-learned-cls C S
  λC S. remove-cls C S λ- -. True invNOT
  λ- S. conflicting S = None backjump-l-cond
  by unfold-locales

```

```

sublocale cdclW ⊆ cdclNOT-merge-bj-learn
  λS. convert-trail-from-W (trail S)
  clauses
  λL S. cons-trail (convert-marked-lit-from-NOT L) S
  λS. tl-trail S
  λC S. add-learned-cls C S
  λC S. remove-cls C S λ- -. True invNOT
  λ- S. conflicting S = None backjump-l-cond
  apply unfold-locales
    using dpll-bj-no-dup apply (simp add: comp-def)
  using cdclNOT-no-dup by (auto simp add: comp-def cdclNOT.simps)

```

```

context cdclW
begin

```

Notations are lost while proving locale inclusion:

notation state-eq_{NOT} (**infix** ~_{NOT} 50)

19.2 Additional Lemmas between NOT and W states

```

lemma trailW-eq-reduce-trail-toNOT-eq:
  trail S = trail T ⇒ trail (reduce-trail-toNOT F S) = trail (reduce-trail-toNOT F T)
proof (induction F S arbitrary: T rule: reduce-trail-toNOT.induct)
  case (1 F S T) note IH = this(1) and tr = this(2)
  then have [] = convert-trail-from-W (trail S)
    ∨ length F = length (convert-trail-from-W (trail S))
    ∨ trail (reduce-trail-toNOT F (tl-trail S)) = trail (reduce-trail-toNOT F (tl-trail T))
    using IH by (metis (no-types) trail-tl-trail)
  then show trail (reduce-trail-toNOT F S) = trail (reduce-trail-toNOT F T)
    using tr by (metis (no-types) reduce-trail-toNOT.elims)
qed

```

lemma *trail-reduce-trail-to_{NOT}-add-learned-cls*:
no-dup (trail S) \implies
 trail (reduce-trail-to_{NOT} M (add-learned-cls D S)) = trail (reduce-trail-to_{NOT} M S)
by (rule trail_W-eq-reduce-trail-to_{NOT}-eq) simp

lemma *reduce-trail-to_{NOT}-reduce-trail-convert*:
 reduce-trail-to_{NOT} C S = reduce-trail-to (convert-trail-from-NOT C) S
apply (induction C S rule: reduce-trail-to_{NOT}.induct)
apply (subst reduce-trail-to_{NOT}.simps, subst reduce-trail-to.simps)
by auto

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 (rename-tac F S ; case-tac trail $S \neq []$; case-tac length (trail S) \neq length M')
by (simp-all add: reduce-trail-to-length-ne)

19.3 More lemmas conflict-propagate and backjumping

19.3.1 Termination

lemma *cdcl_W-cp-normalized-element-all-inv*:
assumes inv: cdcl_W-all-struct-inv S
obtains T **where** full cdcl_W-cp S T
using assms cdcl_W-cp-normalized-element **unfolding** cdcl_W-all-struct-inv-def **by** blast
thm backtrackE

lemma *cdcl_W-bj-measure*:
assumes cdcl_W-bj S T **and** cdcl_W-M-level-inv S
shows length (trail S) + (if conflicting S = None then 0 else 1)
 > length (trail T) + (if conflicting T = None then 0 else 1)
using assms **by** (induction rule: cdcl_W-bj.induct)
 (force dest:arg-cong[of - - length])
 intro: get-all-marked-decomposition-exists-prepend
 elim!: backtrack-levE
 simp: cdcl_W-M-level-inv-def)+

lemma *wf-cdcl_W-bj*:
 wf {(b,a). cdcl_W-bj a b \wedge cdcl_W-M-level-inv a }
apply (rule wfP-if-measure[of λ -. True
 - λT . length (trail T) + (if conflicting T = None then 0 else 1), simplified])
using cdcl_W-bj-measure **by** blast

lemma *cdcl_W-bj-exists-normal-form*:
assumes lev: cdcl_W-M-level-inv S
shows $\exists T$. full cdcl_W-bj S T
proof –
obtain T **where** T : full (λa b . cdcl_W-bj a b \wedge cdcl_W-M-level-inv a) S T
using wf-exists-normal-form-full[OF wf-cdcl_W-bj] **by** auto
then have cdcl_W-bj** S T
by (auto dest: rtrancp-and-rtrancp-left simp: full-def)
moreover
then have cdcl_W** S T
using mono-rtrancp[of cdcl_W-bj cdcl_W] cdcl_W.simps **by** blast
then have cdcl_W-M-level-inv T

using *rtrancpl-cdcl_W-consistent-inv lev* **by** *auto*
ultimately show *?thesis* **using** *T unfolding full-def* **by** *auto*
qed

lemma *rtrancpl-skip-state-decomp*:
assumes *skip** S T* **and** *no-dup (trail S)*
shows
 $\exists M. \text{trail } S = M @ \text{trail } T \wedge (\forall m \in \text{set } M. \neg \text{is-marked } m)$ **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 state-access-simp)

19.3.2 More backjumping

Backjumping after skipping or jump directly **lemma** *rtrancpl-skip-backtrack-backtrack*:

assumes
*skip** S T* **and**
backtrack T W **and**
cdcl_W-all-struct-inv S
shows *backtrack S W*
using *assms*
proof *induction*
case *base*
then show *?case* **by** *simp*
next
case (*step T V*) **note** *st = this(1)* **and** *skip = this(2)* **and** *IH = this(3)* **and** *bt = this(4)* **and**
inv = this(5)
have *skip** S V*
using *st skip* **by** *auto*
then have *cdcl_W-all-struct-inv V*
using *rtrancpl-mono[of skip cdcl_W]* *assms(3) rtrancpl-cdcl_W-all-struct-inv-inv mono-rtrancpl*
by (*auto dest!: bj other cdcl_W-bj.skip*)
then have *cdcl_W-M-level-inv V*
unfolding *cdcl_W-all-struct-inv-def* **by** *auto*
then obtain *N k M1 M2 K D L U i* **where**
 $V: \text{state } V = (\text{trail } V, N, U, k, \text{Some } (D + \{\#L\#}))$ **and**
 $W: \text{state } W = (\text{Propagated } L (D + \{\#L\#}) \# M1, N, \{\#D + \{\#L\# \# \} + U,$
 $\text{get-maximum-level } (\text{trail } V) D, \text{None})$ **and**
 $\text{decomp: } (\text{Marked } K (\text{Suc } i) \# M1, M2)$
 $\in \text{set } (\text{get-all-marked-decomposition } (\text{trail } V))$ **and**
 $k = \text{get-maximum-level } (\text{trail } V) (D + \{\#L\#})$ **and**
 $\text{lev-}L: \text{get-level } (\text{trail } V) L = k$ **and**
 $\text{undef: undefined-lit } M1 L$ **and**
 $W \sim \text{cons-trail } (\text{Propagated } L (D + \{\#L\#}))$
 $(\text{reduce-trail-to } M1 (\text{add-learned-cls } (D + \{\#L\#}))$
 $(\text{update-backtrack-lvl } (\text{get-maximum-level } (\text{trail } V) D) (\text{update-conflicting } \text{None } V))))$ **and**
 $\text{lev-l-}D: \text{backtrack-lvl } V = \text{get-maximum-level } (\text{trail } V) (D + \{\#L\#})$ **and**
 $\text{conflicting } V = \text{Some } (D + \{\#L\#})$ **and**
 $i: i = \text{get-maximum-level } (\text{trail } V) D$
using *bt* **by** (*elim backtrack-levE*)
(auto simp: cdcl_W-M-level-inv-decomp state-eq-def simp del: state-simp)+
let *?D = (D + {\#L\#})*
obtain *L' C'* **where**
 $T: \text{state } T = (\text{Propagated } L' C' \# \text{trail } V, N, U, k, \text{Some } ?D)$ **and**
 $V \sim \text{tl-trail } T$ **and**
 $-L' \notin \# ?D$ **and**


```

?D ≠ {#}
using skip V by force

let ?M = Propagated L' C' # trail V
have cdclW** S T using bj cdclW-bj.skip mono-rtrancp[of skip cdclW S T] other st by meson
then have inv': cdclW-all-struct-inv T
  using rtrancp-cdclW-all-struct-inv-inv inv by blast
have M-lev: cdclW-M-level-inv T using inv' unfolding cdclW-all-struct-inv-def by auto
then have n-d': no-dup ?M
  using T unfolding cdclW-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 state-access-simp)
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 None 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 ?M L = 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 ?M L = get-maximum-level ?M (D + {#L#})
    using lev-l-D[symmetric] L-L' V lev-L by simp
moreover have i = get-maximum-level ?M D

```

using $i \langle \text{atm-of } L' \notin \text{atms-of } D \rangle$ **by** *auto*
moreover

ultimately have *backtrack* $T \ W$
using $T(1) \ W\text{-}S$ **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 $\text{set } (\text{map } \text{fst } (\text{get-all-marked-decomposition } M))$
 $= \text{set } (\text{map } \text{fst } (\text{get-all-marked-decomposition } (MS @ M)))$
using *assms apply (induction MS rule: marked-lit-list-induct)*
apply *auto[2]*
by *(rename-tac L m xs; 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: $\text{skip}^{**} \ S \ T$ **and**
bt: $\text{backtrack} \ S \ W$ **and**
inv: $\text{cdcl}_W\text{-all-struct-inv} \ S$
shows $\text{backtrack} \ T \ W$
using *assms*

proof –

have $M\text{-lev}$: $\text{cdcl}_W\text{-}M\text{-level-inv} \ S$
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 : $\text{state } S = (M, N, U, k, \text{Some } (D + \{\#L\#}))$ **and**
 W : $\text{state } W = (\text{Propagated } L \ (D + \{\#L\#}) \ \# \ M1, N, \{\#D + \{\#L\#\}\# \} + U, \text{get-maximum-level } M \ D,$
 $\text{None})$ **and**
 decomp : $(\text{Marked } K \ (i+1) \ \# \ M1, M2) \in \text{set } (\text{get-all-marked-decomposition } M)$ **and**
 lev-l : $\text{get-level } M \ L = k$ **and**
 lev-l-D : $\text{get-level } M \ L = \text{get-maximum-level } M \ (D + \{\#L\#})$ **and**
 i : $i = \text{get-maximum-level } M \ D$ **and**
 undef : $\text{undefined-lit } M1 \ L$
using *bt by (elim backtrack-levE)*
 $(\text{simp-all add: cdcl}_W\text{-}M\text{-level-inv-decomp state-eq-def del: state-simp})$
let $?D = (D + \{\#L\#})$

have $[\text{simp}]$: $\text{no-dup } (\text{trail } S)$
using $M\text{-lev}$ **by** *(auto simp: cdcl_W-M-level-inv-decomp)*
have $\text{cdcl}_W\text{-all-struct-inv} \ T$
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 $[\text{simp}]$: $\text{no-dup } (\text{trail } T)$
unfolding $\text{cdcl}_W\text{-all-struct-inv-def cdcl}_W\text{-}M\text{-level-inv-def}$ **by** *auto*

obtain $MS \ M_T$ **where** $M: M = MS @ M_T$ **and** $M_T: M_T = \text{trail } T$ **and** $nm: \forall m \in \text{set } MS. \neg \text{is-marked } m$

using *rtrancpl-skip-state-decomp(1)[OF skip] S M-lev by auto*
have T : $\text{state } T = (M_T, N, U, k, \text{Some } ?D)$
using $M_T \ \text{rtrancpl-skip-state-decomp}(2)[\text{of } S \ T] \ \text{skip } S$
by *(auto simp del: state-eq-def state-access-simp)*

```

have cdclW-all-struct-inv T
  apply (rule rtrancp-cdclW-all-struct-inv-inv[OF - inv])
  using bj cdclW-bj.skip local.skip other rtrancp-mono[of skip cdclW] by blast
then have MT ⊨as CNot ?D
  unfolding cdclW-all-struct-inv-def cdclW-conflicting-def using T by blast
have ∀ L ∈ # ?D. atm-of L ∈ atm-of ' lits-of MT
proof -
  have f1: ∧ l. ¬ MT ⊨a {#- l#} ∨ atm-of l ∈ atm-of ' lits-of MT
    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 MT
    using ⟨MT ⊨as CNot (D + {#L#})⟩ multi-member-split by fastforce
  then show ?thesis
    using f1 by (meson ⟨MT ⊨as CNot (D + {#L#})⟩ 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 ∀ L ∈ # ?D. atm-of L ∉ atm-of ' lits-of MS
  unfolding M unfolding lits-of-def by auto
then have H: ∧ L. L ∈ # ?D ⇒ get-level M L = get-level MT L
  unfolding M by (fastforce simp: lits-of-def)
have [simp]: get-maximum-level M ?D = get-maximum-level MT ?D
  by (metis ⟨MT ⊨as CNot (D + {#L#})⟩ M nm ball-msetI true-annots-CNot-all-atms-defined
    get-maximum-level-skip-un-marked-not-present)

have lev-l': get-level MT L = 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 ∼ cons-trail (Propagated L (D + {#L#})) (reduce-trail-to M1
  (add-learned-cls (D + {#L#}) (update-backtrack-lvl i (update-conflicting None T))))
  using W T i decomp undef by (auto simp del: state-simp simp: state-eq-def)

have lev-l-D': get-level MT L = get-maximum-level MT (D + {#L#})
  using lev-l-D by (auto simp: H)
have [simp]: get-maximum-level M D = get-maximum-level MT D
proof -
  have ∧ ms m. ¬ (ms::('v, nat, 'v literal multiset) marked-lit list) ⊨as CNot m
    ∨ (∀ l ∈ # m. atm-of l ∈ atm-of ' lits-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 ∀ l ∈ # D. atm-of l ∈ atm-of ' lits-of MT
    using ⟨MT ⊨as CNot (D + {#L#})⟩ 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 MT D
  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
    ∨ (∃ U. skip-or-resolve** S U ∧ 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  $\implies$  skip S U  $\implies$  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  $\sim$  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, Some (D + {#L#})) and
    decomp: (Marked K (i+1) # M1, M2)  $\in$  set (get-all-marked-decomposition M) and
    get-level M L = k and

```

```

get-level M L = get-maximum-level M (D+{#L#}) and
get-maximum-level M D = i and
T: state T = (Propagated L ( (D+{#L#})) # M1 , N, {#D + {#L#}#} + U', i, None) and
undef: undefined-lit M1 L
using bt-T by (elim backtrack-levE)
(force simp: cdclW-M-level-inv-def state-eq-def simp del: state-simp)+

obtain D' L' i' K' M1' M2' where
S': state S = (M, N, U', k, Some (D' + {#L'#})) and
decomp': (Marked K' (i'+1) # M1', M2') ∈ set (get-all-marked-decomposition M) and
get-level M L' = k and
get-level M L' = get-maximum-level M (D'+{#L'#}) and
get-maximum-level M D' = i' and
U: state U = (Propagated L' (D'+{#L'#}) # M1', N, {#D' + {#L'#}#} + U', i', None) and
undef: undefined-lit M1' L'
using bt-U lev S by (elim backtrack-levE)
(force simp: cdclW-M-level-inv-def state-eq-def simp del: state-simp)+
obtain c where M: M = c @ M2 @ Marked K (i + 1) # M1
using decomp by auto
obtain c' where M': M = c' @ M2' @ Marked K' (i' + 1) # M1'
using decomp' by auto
have marked: get-all-levels-of-marked M = rev [1..l+k]
using inv S unfolding cdclW-all-struct-inv-def cdclW-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 [simp]: L = L'
proof (rule ccontr)
assume ¬ ?thesis
then have L' ∈ # D
using S unfolding S' by (fastforce simp: multiset-eq-iff split: split-if-asm)
then have get-maximum-level M D ≥ k
using ⟨get-level M L' = k⟩ get-maximum-level-ge-get-level by blast
then show False using ⟨get-maximum-level M D = i⟩ ⟨i < k⟩ by auto
qed
then have [simp]: D = D'
using S S' by auto
have [simp]: i=i' using ⟨get-maximum-level M D' = i'⟩ ⟨get-maximum-level M D = i⟩ by auto

```

Automation in a step later...

```

have H: ∧a A B. insert a A = B ⇒ a : B
by blast
have get-all-levels-of-marked (c@M2) = rev [i+2..l+k] and
get-all-levels-of-marked (c'@M2') = rev [i+2..l+k]
using marked unfolding M
using marked unfolding M'
unfolding rev-swap[symmetric] by (auto dest: append-cons-eq-upt-length-i-end)
from arg-cong[OF this(1), of set] arg-cong[OF this(2), of set]
have
dropWhile (λL. ¬is-marked L ∨ level-of L ≠ Suc i) (c @ M2) = [] and
dropWhile (λL. ¬is-marked L ∨ level-of L ≠ Suc i) (c' @ M2') = []
unfolding dropWhile-eq-Nil-conv Ball-def
by (intro allI; rename-tac x; case-tac x; auto dest!: H simp add: in-set-conv-decomp)+

```

then have $M1 = M1'$
using *arg-cong*[*OF M*, *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** (*auto simp del: state-simp simp: state-eq-def*)
qed

lemma *if-can-apply-backtrack-no-more-resolve*:
assumes
skip: $\text{skip}^{**} \ S \ U$ **and**
bt: $\text{backtrack } S \ T$ **and**
inv: $\text{cdcl}_W\text{-all-struct-inv } S$
shows $\neg \text{resolve } U \ V$
proof (*rule ccontr*)
assume *resolve*: $\neg \neg \text{resolve } U \ V$

obtain $L \ C \ M \ N \ U' \ k \ D$ **where**
 U : $\text{state } U = (\text{Propagated } L \ (C + \{\#L\#})) \ \# \ M, N, U', k, \text{Some } (D + \{\#-L\#})$ **and**
 $\text{get-maximum-level } (\text{Propagated } L \ (C + \{\#L\#})) \ \# \ M) \ D = k$ **and**
 $\text{state } V = (M, N, U', k, \text{Some } (D \ \# \cup C))$
using *resolve* **by** *auto*
have $\text{cdcl}_W\text{-all-struct-inv } U$
using *mono-rtrancpl*[*of skip cdcl_W*] **by** (*meson bj cdcl_W-bj.skip inv local.skip other*
rtrancpl-cdcl_W-all-struct-inv-inv)
then have [*iff*]: $\text{no-dup } (\text{trail } S) \ \text{cdcl}_W\text{-M-level-inv } S$ **and** [*iff*]: $\text{no-dup } (\text{trail } U)$
using *inv* **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def } \text{cdcl}_W\text{-M-level-inv-def}$ **by** *blast+*
then have
 S : $\text{init-clss } S = N$
 $\text{learned-clss } S = U'$
 $\text{backtrack-lvl } S = k$
 $\text{conflicting } S = \text{Some } (D + \{\#-L\#})$
using *rtrancpl-skip-state-decomp*(2)[*OF skip*] U
by (*auto simp del: state-simp simp: state-eq-def state-access-simp*)
obtain M_0 **where**
 $\text{tr-}S$: $\text{trail } S = M_0 \ @ \ \text{trail } U$ **and**
 nm : $\forall m \in \text{set } M_0. \neg \text{is-marked } m$
using *rtrancpl-skip-state-decomp*[*OF skip*] **by** *blast*

obtain $M' \ D' \ L' \ i \ K \ M1 \ M2$ **where**
 S' : $\text{state } S = (M', N, U', k, \text{Some } (D' + \{\#L'\#}))$ **and**
 decomp : $(\text{Marked } K \ (i+1) \ \# \ M1, M2) \in \text{set } (\text{get-all-marked-decomposition } M')$ **and**
 $\text{get-level } M' \ L' = k$ **and**
 $\text{get-level } M' \ L' = \text{get-maximum-level } M' \ (D' + \{\#L'\#})$ **and**
 $\text{get-maximum-level } M' \ D' = i$ **and**
 undef : $\text{undefined-lit } M1 \ L'$ **and**
 T : $\text{state } T = (\text{Propagated } L' \ (D' + \{\#L'\#})) \ \# \ M1, N, \{\#D' + \{\#L'\#\}\# + U', i, \text{None})$
using *bt* **by** (*elim backtrack-levE*) (*fastforce simp: S state-eq-def simp del: state-simp*) +
obtain c **where** M : $M' = c \ @ \ M2 \ @ \ \text{Marked } K \ (i+1) \ \# \ M1$
using *get-all-marked-decomposition-exists-prepend*[*OF decomp*] **by** *auto*
have marked : $\text{get-all-levels-of-marked } M' = \text{rev } [1..<1+k]$
using *inv* S' **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def } \text{cdcl}_W\text{-M-level-inv-def}$ **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 [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  $tr-S \ U \ S \ S'$  by (auto simp: lits-of-def)
    have no-dup  $M'$ 
      using  $inv \ U \ S'$  unfolding  $cdcl_W$ -all-struct-inv-def  $cdcl_W$ -M-level-inv-def by auto
    have atm-L-notin-M: atm-of  $L \notin \text{atm-of } (lits-of \ M)$ 
      using  $\langle no-dup \ M' \rangle \ M' \ U \ S \ S'$  by (auto simp: lits-of-def)
    have get-all-levels-of-marked  $M' = rev [1..<1+k]$ 
      using  $inv \ U \ S'$  unfolding  $cdcl_W$ -all-struct-inv-def  $cdcl_W$ -M-level-inv-def by auto
    then have get-all-levels-of-marked  $M = rev [1..<1+k]$ 
      using  $nm \ M' \ S' \ U$  by (simp add: get-all-levels-of-marked-no-marked)
    then have get-lev-L:
      get-level( $\text{Propagated } L (C + \{\#L\# \}) \# M$ )  $L = k$ 
      using get-level-get-rev-level-get-all-levels-of-marked[OF atm-L-notin-M,
        of [ $\text{Propagated } L ((C + \{\#L\# \}))$ ]] by simp
    have atm-of  $L \notin \text{atm-of } (lits-of (rev \ M_0))$ 
      using  $\langle no-dup \ M' \rangle \ M' \ U \ S'$  by (auto simp: lits-of-def)
    then have get-level  $M' \ L = k$ 
      using get-rev-level-notin-end[of  $L \ rev \ M_0$ 
         $rev \ M @ \text{Propagated } L (C + \{\#L\# \}) \# [] \ 0$ ]
      using  $tr-S \ get-lev-L \ M' \ U \ S'$  by (simp add: nm lits-of-def)
    ultimately have get-maximum-level  $M' \ D' \geq k$ 
      by (metis get-maximum-level-ge-get-level get-rev-level-uminus)
    then show False
      using  $\langle i < k \rangle$  unfolding  $\langle get-maximum-level \ M' \ D' = i \rangle$  by auto
qed
have [simp]:  $D = D'$  using  $DD'$  by auto
have  $cdcl_W^{**} \ S \ U$ 
  using  $bj \ cdcl_W$ -bj.skip local.skip mono-rtrancpl[of skip  $cdcl_W \ S \ U$ ] other by meson
then have  $cdcl_W$ -all-struct-inv  $U$ 
  using  $inv \ rtrancpl$ - $cdcl_W$ -all-struct-inv-inv by blast
then have  $\text{Propagated } L ( (C + \{\#L\# \}) ) \# M \models_{as} CNot (D' + \{\#L\# \})$ 
  using  $cdcl_W$ -all-struct-inv-def  $cdcl_W$ -conflicting-def  $U$  by auto
then have  $\forall L' \in \# D. \text{atm-of } L' \in \text{atm-of } (lits-of (\text{Propagated } L ( (C + \{\#L\# \}) ) \# M))$ 
  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  $M' \ D = k$ 
  using  $tr-S \ nm \ U \ S'$ 
  get-maximum-level-skip-un-marked-not-present[of  $D$ 
     $\text{Propagated } L (C + \{\#L\# \}) \# M \ M_0$ ]
  unfolding  $\langle get-maximum-level (\text{Propagated } L (C + \{\#L\# \}) \# M) \ D = k \rangle$ 
  unfolding  $\langle D = D' \rangle$ 
  by simp
then show False
  using  $\langle get-maximum-level \ M' \ D' = i \rangle \ \langle i < k \rangle$  by auto
qed

```

lemma if-can-apply-resolve-no-more-backtrack:

assumes
skip: $\text{skip}^{**} S U$ **and**
resolve: $\text{resolve } S T$ **and**
inv: $\text{cdcl}_W\text{-all-struct-inv } S$
shows $\neg \text{backtrack } U V$
using *assms*
by (*meson if-can-apply-backtrack-no-more-resolve rtrancpl.rtrancpl-refl*
rtrancpl-skip-backtrack-backtrack)

lemma *if-can-apply-backtrack-skip-or-resolve-is-skip*:

assumes
bt: $\text{backtrack } S T$ **and**
skip: $\text{skip-or-resolve}^{**} S U$ **and**
inv: $\text{cdcl}_W\text{-all-struct-inv } S$
shows $\text{skip}^{**} S U$
using *assms*(2,3,1)
by *induction (simp-all add: if-can-apply-backtrack-no-more-resolve)*

lemma *cdcl_W-bj-bj-decomp*:

assumes $\text{cdcl}_W\text{-bj}^{**} S W$ **and** $\text{cdcl}_W\text{-all-struct-inv } S$
shows
 $(\exists T U V. (\lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S)^{**} S T$
 $\wedge (\lambda T U. \text{resolve } T U \wedge \text{no-step backtrack } T) T U$
 $\wedge \text{skip}^{**} U V \wedge \text{backtrack } V W)$
 $\vee (\exists T U. (\lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S)^{**} S T$
 $\wedge (\lambda T U. \text{resolve } T U \wedge \text{no-step backtrack } T) T U \wedge \text{skip}^{**} U W)$
 $\vee (\exists T. \text{skip}^{**} S T \wedge \text{backtrack } T W)$
 $\vee \text{skip}^{**} S W$ (**is** $?RB S W \vee ?R S W \vee ?SB S W \vee ?S S W$)
using *assms*

proof *induction*

case *base*

then show *?case* **by** *simp*

next

case (*step* $W X$) **note** $st = \text{this}(1)$ **and** $bj = \text{this}(2)$ **and** $IH = \text{this}(3)[OF \text{this}(4)]$ **and** $inv = \text{this}(4)$

have $\neg ?RB S W$ **and** $\neg ?SB S W$

proof (*clarify, goal-cases*)

case (*1* $T U V$)

have $\text{skip-or-resolve}^{**} S T$

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-cdcl_W-bj*
cdcl_W-all-struct-inv-def cdcl_W-all-struct-inv-inv cdcl_W-o.bj local.bj other
resolve rtrancpl-cdcl_W-all-struct-inv-inv rtrancpl-skip-backtrack-backtrack
rtrancpl-skip-or-resolve-rtrancpl-cdcl_W step.premis)

next

case *2*

then show *?case* **by** (*meson assms(2) cdcl_W-all-struct-inv-def backtrack-no-cdcl_W-bj*
local.bj rtrancpl-skip-backtrack-backtrack)

qed

then have $IH: ?R S W \vee ?S S W$ **using** IH **by** *blast*

have $\text{cdcl}_W^{**} S W$ **by** (*metis cdcl_W-o.bj mono-rtrancpl other st*)

then have $inv\text{-}W: \text{cdcl}_W\text{-all-struct-inv } W$ **by** (*simp add: rtrancpl-cdcl_W-all-struct-inv-inv*
step.premis)


```

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
    (λS T. skip-or-resolve S T ∧ 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 (λS T. skip-or-resolve S T ∧ 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.premis)
  { fix U'
    assume skip** U U' and skip** U' W
    have cdclW-all-struct-inv U'
    using ⟨cdclW-all-struct-inv U⟩ ⟨skip** U U'⟩ 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 ⟨skip** U' W⟩] res by blast
  }
  with ⟨skip** U W⟩
  have (λS T. skip-or-resolve S T ∧ 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.premis)
  ultimately show ?case by simp
qed
then show ?thesis
proof -
  have f1:  $\forall p pa pb pc. \neg p (pa) pb \vee \neg p^{**} pb pc \vee p^{**} pa pc$ 
    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  $(\lambda p pa. \text{skip-or-resolve } p pa \wedge \text{no-step backtrack } p)^{**} T W$ 
  proof -
    have  $(\exists vr19 vr16 vr17 vr18. vr19 (vr16::'st) vr17 \wedge vr19^{**} vr17 vr18$ 
       $\wedge \neg vr19^{**} vr16 vr18)$ 
       $\vee \neg (\text{skip-or-resolve } T U \wedge \text{no-step backtrack } T)$ 
       $\vee \neg (\lambda uu uua. \text{skip-or-resolve } uu uua \wedge \text{no-step backtrack } uu)^{**} U W$ 
       $\vee (\lambda uu uua. \text{skip-or-resolve } uu uua \wedge \text{no-step backtrack } uu)^{**} T W$ 
    by force
    then show ?thesis
      by (metis (no-types)  $\langle \lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S \rangle^{**} U W$ 
         $\langle \text{skip-or-resolve } T U \wedge \text{no-step backtrack } T \rangle f1$ )
  qed
  then have  $(\lambda p pa. \text{skip-or-resolve } p pa \wedge \text{no-step backtrack } p)^{**} S W$ 
    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)  $\langle \text{cdcl}_W\text{-all-struct-inv } S \rangle$ 
      rtrancpl-cdclW-all-struct-inv-inv)
  then have no-step backtrack U'
    using if-can-apply-backtrack-no-more-resolve[OF  $\langle \text{skip}^{**} U' W \rangle$ ] res by blast
}
with S
have  $(\lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S)^{**} S W$ 
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 ( $\lambda S T. \text{skip-or-resolve } S T \wedge \text{no-step backtrack } S$ )**  $S V$ 
      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.premis)
    ultimately show ?case by simp
  qed
  then show ?thesis using res no-bt by blast
qed
qed
qed

```

The case distinction is needed, since $T \sim V$ does not imply that $R^{**} T V$.

lemma *cdcl_W-bj-strongly-confluent*:

```

  assumes
    cdclW-bj**  $S V$  and
    cdclW-bj**  $S T$  and
    n-s: no-step cdclW-bj  $V$  and
    inv: cdclW-all-struct-inv  $S$ 
  shows  $T \sim V \vee \text{cdcl}_W\text{-bj}^{**} T V$ 
  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-o-r = this(2) and IH = this(3)
  have cdclW**  $S T$ 
    using st mono-rtrancpl[of cdclW-bj cdclW] other by blast
  then have lev-T: cdclW-M-level-inv  $T$ 
    using inv rtrancpl-cdclW-consistent-inv[of  $S T$ ]
  unfolding cdclW-all-struct-inv-def by auto

```

consider

```

  (TV)  $T \sim V$ 
  | (bj-TV) cdclW-bj**  $T V$ 
  using IH by blast
then show ?case
proof cases
  case TV
  have no-step cdclW-bj  $T$ 
    using  $\langle \text{cdcl}_W\text{-M-level-inv } T \rangle$  n-s cdclW-bj-state-eq-compatible[of  $T - V$ ] TV by auto
  then show ?thesis
    using s-o-r by auto
next
  case bj-TV
  then obtain  $U'$  where
     $T-U'$ : cdclW-bj  $T U'$  and
    cdclW-bj**  $U' V$ 
    using IH n-s s-o-r by (metis rtrancpl-unfold trancplD)
  have cdclW**  $S T$ 
    by (metis (no-types, hide-lams) bj mono-rtrancpl[of cdclW-bj cdclW] other st)
  then have inv-T: cdclW-all-struct-inv  $T$ 
    by (metis (no-types, hide-lams) inv rtrancpl-cdclW-all-struct-inv-inv)

```

```

have lev-U: cdclW-M-level-inv U
  using s-o-r cdclW-consistent-inv lev-T other by blast
show ?thesis
  using s-o-r
  proof cases
    case backtrack
      then obtain V0 where skip** T V0 and backtrack V0 V
        using IH if-can-apply-backtrack-skip-or-resolve-is-skip[OF backtrack - inv-T]
          cdclW-bj-decomp-resolve-skip-and-bj
          by (meson bj-TV cdclW-bj.backtrack inv-T lev-T n-s
            rtrancpl-skip-backtrack-backtrack-end)
      then have cdclW-bj** T V0 and cdclW-bj V0 V
        using rtrancpl-mono[of skip cdclW-bj] by blast+
      then show ?thesis
        using ⟨backtrack V0 V⟩ ⟨skip** T V0⟩ backtrack-unique inv-T local.backtrack
          rtrancpl-skip-backtrack-backtrack by auto
    next
      case resolve
        then have U ~ U'
          by (meson T-U' cdclW-bj.simps if-can-apply-backtrack-no-more-resolve inv-T
            resolve-skip-deterministic resolve-unique rtrancpl.rtrancpl-refl)
        then show ?thesis
          using ⟨cdclW-bj** U' V⟩ unfolding rtrancpl-unfold
          by (meson T-U' bj cdclW-consistent-inv lev-T other state-eq-ref state-eq-sym
            trancpl-cdclW-bj-state-eq-compatible)
    next
      case skip
        consider
          (sk) skip T U'
          | (bt) backtrack T U'
        using T-U' by (meson cdclW-bj.cases local.skip resolve-skip-deterministic)
        then show ?thesis
          proof cases
            case sk
              then show ?thesis
                using ⟨cdclW-bj** U' V⟩ unfolding rtrancpl-unfold
                by (meson T-U' bj cdclW-all-inv(3) cdclW-all-struct-inv-def inv-T local.skip other
                  trancpl-cdclW-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 ⟨cdclW-bj** U' V⟩ backtrack inv-T trancpl-unfold-begin
                    rtrancpl-skip-backtrack-backtrack-end trancpl-into-rtrancpl)
          qed
        qed
      qed
    qed
  qed

```

lemma *cdcl_W-bj-unique-normal-form*:
assumes
ST: *cdcl_W-bj** S T* and *SU*: *cdcl_W-bj** S U* and
n-s-U: *no-step cdcl_W-bj U* and

$n\text{-}s\text{-}T$: $\text{no-step } \text{cdcl}_W\text{-bj } T$ **and**
 inv : $\text{cdcl}_W\text{-all-struct-inv } S$
shows $T \sim U$
proof –
have $T \sim U \vee \text{cdcl}_W\text{-bj}^{**} T U$
using $ST\ SU\ \text{cdcl}_W\text{-bj-strongly-confluent inv } n\text{-}s\text{-}U$ **by** *blast*
then show *?thesis*
by (*metis* (*no-types*) $n\text{-}s\text{-}T\ \text{rtranclp-unfold state-eq-ref tranclp-unfold-begin}$)
qed

lemma $\text{full-cdcl}_W\text{-bj-unique-normal-form}$:
assumes $\text{full } \text{cdcl}_W\text{-bj } S\ T$ **and** $\text{full } \text{cdcl}_W\text{-bj } S\ U$ **and**
 inv : $\text{cdcl}_W\text{-all-struct-inv } S$
shows $T \sim U$
using $\text{cdcl}_W\text{-bj-unique-normal-form assms unfolding full-def}$ **by** *blast*

19.4 CDCL FW

inductive $\text{cdcl}_W\text{-merge-restart} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **where**
 fw-r-propagate : $\text{propagate } S\ S' \Longrightarrow \text{cdcl}_W\text{-merge-restart } S\ S' \mid$
 fw-r-conflict : $\text{conflict } S\ T \Longrightarrow \text{full } \text{cdcl}_W\text{-bj } T\ U \Longrightarrow \text{cdcl}_W\text{-merge-restart } S\ U \mid$
 fw-r-decide : $\text{decide } S\ S' \Longrightarrow \text{cdcl}_W\text{-merge-restart } S\ S' \mid$
 fw-r-rf : $\text{cdcl}_W\text{-rf } S\ S' \Longrightarrow \text{cdcl}_W\text{-merge-restart } S\ S'$

lemma $\text{cdcl}_W\text{-merge-restart-cdcl}_W$:
assumes $\text{cdcl}_W\text{-merge-restart } S\ T$
shows $\text{cdcl}_W^{**} S\ T$
using *assms*
proof *induction*
case ($\text{fw-r-conflict } S\ T\ U$) **note** $\text{confl} = \text{this}(1)$ **and** $\text{bj} = \text{this}(2)$
have $\text{cdcl}_W\ S\ T$ **using** confl **by** (*simp add: cdcl_W.intros r-into-rtranclp*)
moreover
have $\text{cdcl}_W\text{-bj}^{**} T\ U$ **using** bj **unfolding** *full-def* **by** *auto*
then have $\text{cdcl}_W^{**} T\ U$ **by** (*metis cdcl_W-o.bj mono-rtranclp other*)
ultimately show *?case* **by** *auto*
qed (*simp-all add: cdcl_W-o.intros cdcl_W.intros r-into-rtranclp*)

lemma $\text{cdcl}_W\text{-merge-restart-conflicting-true-or-no-step}$:
assumes $\text{cdcl}_W\text{-merge-restart } S\ T$
shows $\text{conflicting } T = \text{None} \vee \text{no-step } \text{cdcl}_W\ T$
using *assms*
proof *induction*
case ($\text{fw-r-conflict } S\ T\ U$) **note** $\text{confl} = \text{this}(1)$ **and** $n\text{-}s = \text{this}(2)$
{ fix $D\ V$
assume $\text{cdcl}_W\ U\ V$ **and** $\text{conflicting } U = \text{Some } D$
then have *False*
using $n\text{-}s$ **unfolding** *full-def*
by (*induction rule: cdcl_W-all-rules-induct*) (*auto dest!: cdcl_W-bj.intros*)
}
then show *?case* **by** (*cases conflicting U*) *fastforce+*
qed (*auto simp add: cdcl_W-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 : $\text{decide } S\ S' \Longrightarrow \text{cdcl}_W\text{-merge } S\ S'$

fw-forget: $\text{forget } S \ S' \implies \text{cdcl}_W\text{-merge } S \ S'$

lemma *cdcl_W-merge-cdcl_W-merge-restart*:

$\text{cdcl}_W\text{-merge } S \ T \implies \text{cdcl}_W\text{-merge-restart } S \ T$

by (*meson cdcl_W-merge.cases cdcl_W-merge-restart.simps forget*)

lemma *rtrancpl-cdcl_W-merge-rtrancpl-cdcl_W-merge-restart*:

$\text{cdcl}_W\text{-merge}^{**} \ S \ T \implies \text{cdcl}_W\text{-merge-restart}^{**} \ S \ T$

using *rtrancpl-mono*[*of cdcl_W-merge cdcl_W-merge-restart*] *cdcl_W-merge-cdcl_W-merge-restart* **by** *blast*

lemma *cdcl_W-merge-rtrancpl-cdcl_W*:

$\text{cdcl}_W\text{-merge } S \ T \implies \text{cdcl}_W^{**} \ S \ T$

using *cdcl_W-merge-cdcl_W-merge-restart cdcl_W-merge-restart-cdcl_W* **by** *blast*

lemma *rtrancpl-cdcl_W-merge-rtrancpl-cdcl_W*:

$\text{cdcl}_W\text{-merge}^{**} \ S \ T \implies \text{cdcl}_W^{**} \ S \ T$

using *rtrancpl-mono*[*of cdcl_W-merge cdcl_W^{**}*] *cdcl_W-merge-rtrancpl-cdcl_W* **by** *auto*

lemma *cdcl_W-merge-is-cdcl_{NOT}-merged-bj-learn*:

assumes

inv: *cdcl_W-all-struct-inv* *S* **and**

cdcl_W:*cdcl_W-merge* *S* *T*

shows *cdcl_{NOT}-merged-bj-learn* *S* *T*

$\vee (\text{no-step } \text{cdcl}_W\text{-merge } T \wedge \text{conflicting } T \neq \text{None})$

using *cdcl_W 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*, *None*) **and**

CL: *C* + {*#L#*} ∈ *# clauses* *S* **and**

M-C: *M* ⊢_{as} *CNot C* **and**

undef: *undefined-lit* (*trail* *S*) *L* **and**

T: *T* ∼ *cons-trail* (*Propagated* *L* (*C* + {*#L#*})) *S*

using *propa* **by** *auto*

have *propagate_{NOT}* *S* *T*

apply (*rule propagate_{NOT}.propagate_{NOT}*[*of - C L*])

using *H CL T undef M-C* **by** (*auto simp: state-eq_{NOT}-def state-eq-def clauses-def*

simp del: state-simp)

then show *?case*

using *cdcl_{NOT}-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* ∈ *atms-of-msu* (*init-clss* *S*) **and**

T: *T* ∼ *cons-trail* (*Marked* *L* (*Suc* (*backtrack-lvl* *S*)))

(*update-backtrack-lvl* (*Suc* (*backtrack-lvl* *S*)) *S*)

by *auto*

have *decide_{NOT}* *S* *T*

apply (*rule decide_{NOT}.decide_{NOT}*)

using *undef-L* **apply** *simp*

using *atm-L inv unfolding cdcl_W-all-struct-inv-def no-strange-atm-def clauses-def* **apply** *auto*[]

using *T undef-L unfolding state-eq-def state-eq_{NOT}-def* **by** (*auto simp: clauses-def*)

then show *?case* **using** *cdcl_{NOT}-merged-bj-learn-decide_{NOT}* **by** *blast*

next

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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, None) and
   $\neg M \models_{asm} clauses\ S$  and
  C  $\notin$  set (get-all-mark-of-propagated (trail S)) and
  C-init: C  $\notin$  init-clss S and
  C-le: C  $\in$  learned-clss S and
  T: T  $\sim$  remove-cl 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-cl)
then have S-C: clauses S - replicate-mset (count (clauses S) C) C  $\models_{pm} C$ 
  using C-init C-le unfolding clauses-def by (simp add: Un-Diff)
moreover have H: init-clss S + (learned-clss S - replicate-mset (count (learned-clss S) C) C)
  = init-clss S + learned-clss S - replicate-mset (count (learned-clss S) C) C
  using C-le C-init by (metis clauses-def clauses-remove-cl diff-zero grOI
    init-clss-remove-cl learned-clss-remove-cl 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  $\langle C \in \# learned-clss S \rangle$  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)
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 CS where
  confl-T: conflicting T = Some CS and
  CS: CS  $\in$  clauses S and
  tr-S-CS: trail S  $\models_{as} CNot\ C_S$ 
  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' where skip-or-resolve** T T' and backtrack T' U
  using bj rtrancpl-cdclW-bj-skip-or-resolve-backtrack unfolding full-def by meson
then show ?case
proof cases
  case no-bt
    then have conflicting U  $\neq$  None
    using confl by (induction rule: rtrancpl-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-rtrancpl[of skip-or-resolve cdclW] rtrancpl-skip-or-resolve-rtrancpl-cdclW

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  by blast
then have  $cdcl_W$ -M-level-inv  $T'$ 
  using  $rtrancpl$ - $cdcl_W$ -consistent-inv  $\langle cdcl_W$ -M-level-inv  $T \rangle$  by blast
then obtain  $M1$   $M2$   $i$   $D$   $L$   $K$  where
   $confl$ - $T'$ :  $conflicting\ T' = Some\ (D + \{\#L\# \})$  and
   $M1$ - $M2$ :  $(Marked\ K\ (i+1)\ \# \ M1, \ M2) \in set\ (get\_all\_marked\_decomposition\ (trail\ T'))$  and
   $get\_level\ (trail\ T')\ L = backtrack\_lvl\ T'$  and
   $get\_level\ (trail\ T')\ L = get\_maximum\_level\ (trail\ T')\ (D + \{\#L\# \})$  and
   $get\_maximum\_level\ (trail\ T')\ D = i$  and
   $undef$ - $L$ :  $undefined\_lit\ M1\ L$  and
   $U$ :  $U \sim cons\_trail\ (Propagated\ L\ (D + \{\#L\# \}))$ 
    ( $reduce\_trail\_to\ M1$ 
      ( $add\_learned\_cls\ (D + \{\#L\# \})$ 
        ( $update\_backtrack\_lvl\ i$ 
          ( $update\_conflicting\ None\ 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  $inv$ - $T$ :  $cdcl_W$ -all-struct-inv  $T$ 
  by ( $meson\ cdcl_W$ - $cp$ . $simps\ confl\ inv\ r$ -into- $rtrancpl\ rtrancpl$ - $cdcl_W$ -all-struct-inv-inv
     $rtrancpl$ - $cdcl_W$ - $cp$ - $rtrancpl$ - $cdcl_W$ )
have  $cdcl_W^{**}\ T\ T'$ 
  using  $rtrancpl$ -skip-or-resolve- $rtrancpl$ - $cdcl_W\ s-or-r$  by blast
have  $inv$ - $T'$ :  $cdcl_W$ -all-struct-inv  $T'$ 
  using  $\langle cdcl_W^{**}\ T\ T' \rangle\ inv$ - $T\ rtrancpl$ - $cdcl_W$ -all-struct-inv-inv by blast
have  $inv$ - $U$ :  $cdcl_W$ -all-struct-inv  $U$ 
  using  $cdcl_W$ -merge-restart- $cdcl_W\ confl\ fw$ - $r$ -conflict  $inv\ local.bj$ 
   $rtrancpl$ - $cdcl_W$ -all-struct-inv-inv by blast

have  $[simp]$ :  $init\_clss\ S = init\_clss\ T'$ 
  using  $\langle cdcl_W^{**}\ T\ T' \rangle\ cdcl_W$ -init-clss  $confl\ cdcl_W$ -all-struct-inv-def  $confl\ inv$ 
  by ( $metis\ \langle cdcl_W$ -M-level-inv  $T \rangle\ rtrancpl$ - $cdcl_W$ -init-clss)
then have  $atm$ - $L$ :  $atm\_of\ L \in atm\_of\_msu\ (clauses\ S)$ 
  using  $inv$ - $T'$   $confl$ - $T'$  unfolding  $cdcl_W$ -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 ( $induction\ rule$ :  $rtrancpl$ -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  $cdcl_W$ -all-struct-inv-def  $cdcl_W$ -M-level-inv-def
  by fastforce
def  $M'' \equiv M @ M'$ 
  have  $tr$ - $T$ :  $trail\ S = M'' @ Marked\ K\ (i+1)\ \# \ tl\ (trail\ U)$ 

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    using tr-T tr-T' confl unfolding M''-def by auto
have init-clss T' + learned-clss S  $\models_{pm}$  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 add: comp-def)
    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
        trail-reduce-trail-toNOT-add-learned-cls)[]
    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 add: trail-reduce-trail-toNOT-add-learned-cls)
    using (init-clss T' + learned-clss S  $\models_{pm}$  D + {#L#}) unfolding clauses-def apply simp
    apply (metis (tl (trail U)  $\models_{as}$  CNot D) 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 backjump-l-cond-def)
then show ?thesis using cdclNOT-merged-bj-learn-backjump-l by fast
qed
qed

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abbreviation $cdcl_{NOT}$ -restart **where**

$cdcl_{NOT}$ -restart \equiv restart-ops.cdcl_{NOT}-raw-restart cdcl_{NOT} restart

lemma $cdcl_W$ -merge-restart-is-cdcl_{NOT}-merged-bj-learn-restart-no-step:

assumes

inv: cdcl_W-all-struct-inv S **and**

cdcl_W:cdcl_W-merge-restart S T

shows $cdcl_{NOT}$ -restart** S T \vee (no-step cdcl_W-merge T \wedge conflicting T \neq None)

proof –

consider

(fw) cdcl_W-merge S T

| (fw-r) restart S T

using cdcl_W **by** (meson cdcl_W-merge-restart.simps cdcl_W-rf.cases fw-conflict fw-decide fw-forget
fw-propagate)

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then show ?thesis
proof cases
  case fw
  then have IH:  $cdcl_{NOT}$ -merged-bj-learn  $S T \vee (no\text{-}step\ cdcl_W\text{-}merge\ T \wedge conflicting\ T \neq None)$ 
    using inv  $cdcl_W$ -merge-is- $cdcl_{NOT}$ -merged-bj-learn by blast
  have invS:  $inv_{NOT}\ S$ 
    using inv unfolding  $cdcl_W$ -all-struct-inv-def  $cdcl_W$ -M-level-inv-def by auto
  have ff2:  $cdcl_{NOT}^{++}\ S\ T \longrightarrow cdcl_{NOT}^{**}\ S\ T$ 
    by (meson tranclp-into-rtranclp)
  have ff3: no-dup (convert-trail-from-W (trail S))
    using invS by (simp add: comp-def)
  have  $cdcl_{NOT} \leq cdcl_{NOT}$ -restart
    by (auto simp: restart-ops. $cdcl_{NOT}$ -raw-restart.simps)
  then show ?thesis
    using ff3 ff2 IH  $cdcl_{NOT}$ -merged-bj-learn-is-tranclp- $cdcl_{NOT}$ 
    rtranclp-mono[of  $cdcl_{NOT}$   $cdcl_{NOT}$ -restart] invS predicate2D by blast
next
  case fw-r
  then show ?thesis by (blast intro: restart-ops. $cdcl_{NOT}$ -raw-restart.intros)
qed
qed

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abbreviation $\mu_{FW} :: 'st \Rightarrow nat$ **where**
 $\mu_{FW}\ S \equiv (if\ no\text{-}step\ cdcl_W\text{-}merge\ S\ then\ 0\ else\ 1 + \mu_{CDCL}'\text{-}merged\ (set\text{-}mset\ (init\text{-}class\ S))\ S)$

lemma $cdcl_W$ -merge- μ_{FW} -decreasing:

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assumes
  inv:  $cdcl_W$ -all-struct-inv  $S$  and
  fw:  $cdcl_W$ -merge  $S\ T$ 
shows  $\mu_{FW}\ T < \mu_{FW}\ S$ 
proof -
  let ?A = init-class  $S$ 
  have atm-clauses:  $atms\text{-}of\text{-}msu\ (clauses\ S) \subseteq atms\text{-}of\text{-}msu\ ?A$ 
    using inv unfolding  $cdcl_W$ -all-struct-inv-def no-strange-atm-def clauses-def by auto
  have atm-trail:  $atm\text{-}of\ ' lits\text{-}of\ (trail\ S) \subseteq atms\text{-}of\text{-}msu\ ?A$ 
    using inv unfolding  $cdcl_W$ -all-struct-inv-def no-strange-atm-def clauses-def by auto
  have n-d: no-dup (trail S)
    using inv unfolding  $cdcl_W$ -all-struct-inv-def by (auto simp:  $cdcl_W$ -M-level-inv-decomp)
  have [simp]:  $\neg no\text{-}step\ cdcl_W$ -merge  $S$ 
    using fw by auto
  have [simp]: init-class  $S = init\text{-}class\ T$ 
    using  $cdcl_W$ -merge-restart- $cdcl_W$ [of  $S\ T$ ] inv rtranclp- $cdcl_W$ -init-class
    unfolding  $cdcl_W$ -all-struct-inv-def
    by (meson  $cdcl_W$ -merge.simps  $cdcl_W$ -merge-restart.simps  $cdcl_W$ -rf.simps fw)
  consider
    (merged)  $cdcl_{NOT}$ -merged-bj-learn  $S\ T$ 
  | (n-s) no-step  $cdcl_W$ -merge  $T$ 
  using  $cdcl_W$ -merge-is- $cdcl_{NOT}$ -merged-bj-learn inv fw by blast
  then show ?thesis
  proof cases
    case merged
    then show ?thesis
      using  $cdcl_{NOT}$ -decreasing-measure'[OF - - atm-clauses] atm-trail n-d
      by (auto split: split-if simp: comp-def)
  next

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    case  $n-s$ 
    then show ?thesis by simp
qed
qed

lemma wf-cdclW-merge: wf {(T, S). cdclW-all-struct-inv S ∧ cdclW-merge S T}
  apply (rule wfP-if-measure[of - - μFW])
  using cdclW-merge-μFW-decreasing by blast

lemma cdclW-all-struct-inv-tranclp-cdclW-merge-tranclp-cdclW-merge-cdclW-all-struct-inv:
  assumes
    inv: cdclW-all-struct-inv b
    cdclW-merge++ b a
  shows (λS T. cdclW-all-struct-inv S ∧ cdclW-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 cdclW-all-struct-inv c
    using tranclp-into-rtranclp[OF st] cdclW-merge-rtranclp-cdclW
    assms(1) rtranclp-cdclW-all-struct-inv-inv rtranclp-mono[of cdclW-merge cdclW**] by fastforce
  then have (λS T. cdclW-all-struct-inv S ∧ cdclW-merge S T)++ c d
    using fw by auto
  then show ?case using IH by auto
qed

lemma wf-tranclp-cdclW-merge: wf {(T, S). cdclW-all-struct-inv S ∧ cdclW-merge++ S T}
  using wf-trancl[OF wf-cdclW-merge]
  apply (rule wf-subset)
  by (auto simp: trancl-set-tranclp
    cdclW-all-struct-inv-tranclp-cdclW-merge-tranclp-cdclW-merge-cdclW-all-struct-inv)

lemma backtrack-is-full1-cdclW-bj:
  assumes bt: backtrack S T and inv: cdclW-M-level-inv S
  shows full1 cdclW-bj S T
proof -
  have no-step cdclW-bj T
    using bt inv backtrack-no-cdclW-bj by blast
  moreover have cdclW-bj++ S T
    using bt by auto
  ultimately show ?thesis unfolding full1-def by blast
qed

lemma rtrancl-cdclW-conflicting-true-cdclW-merge-restart:
  assumes cdclW** S V and inv: cdclW-M-level-inv S and conflicting S = None
  shows (cdclW-merge-restart** S V ∧ conflicting V = None)
    ∨ (∃ T U. cdclW-merge-restart** S T ∧ conflicting V ≠ None ∧ conflict T U ∧ cdclW-bj** U V)
  using assms
proof induction
  case base
  then show ?case by simp
next
  case (step U V) note st = this(1) and cdclW = this(2) and IH = this(3)[OF this(4-)] and

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  confl[simp] = this(5) and inv = this(4)
from cdclW
show ?case
proof (cases)
  case propagate
  moreover then have conflicting U = None
    by auto
  moreover have conflicting V = None
    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 = None
    by auto
  moreover have conflicting V ≠ None
    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 = None
      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
         $\vee$  cdclW-merge-restart** S T  $\wedge$  conflicting U ≠ None
         $\wedge$  conflict T T'  $\wedge$  cdclW-bj** T' U
    using IH confl by blast
    then have ?thesis
    proof –
      have conflicting V ≠ None  $\wedge$  conflicting U ≠ None
        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 ≠ None by auto
    then obtain T T' where
      cdclW-merge-restart** S T and
      conflicting U ≠ None and
      conflict T T' and
      cdclW-bj** T' U
    using IH confl by meson
    have invU: cdclW-M-level-inv U
      using inv rtranclp-cdclW-consistent-inv step.hyps(1) by blast
  }

```

```

    then have conflicting V = None
      using ⟨backtrack U V⟩ inv by (auto elim: backtrack-levE
        simp: cdclW-M-level-inv-decomp)
    have full cdclW-bj T' V
      apply (rule rtrancpl-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 = None⟩ by auto
  }
  ultimately show ?thesis by (auto simp: cdclW-bj.simps)
qed
next
case rf
moreover then have conflicting U = None and conflicting V = None
  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-cdclW-no-step-cdclW-merge-restart: no-step cdclW S  $\implies$  no-step cdclW-merge-restart S
by (auto simp: cdclW.simps cdclW-merge-restart.simps cdclW-o.simps cdclW-bj.simps)

lemma no-step-cdclW-merge-restart-no-step-cdclW:
  assumes
    conflicting S = None 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 rtrancpl-cdclW-merge-restart-no-step-cdclW-bj:
  assumes
    cdclW-merge-restart** S T and
    conflicting S = None
  shows no-step cdclW-bj T
  using assms
  apply (induction rule: rtrancpl-induct)

```

```

  apply (fastforce simp: cdclW-bj.simps cdclW-rf.simps cdclW-merge-restart.simps full-def)
  apply (fastforce simp: cdclW-bj.simps cdclW-rf.simps cdclW-merge-restart.simps full-def)

done

```

If *conflicting* $S \neq \text{None}$, 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 confl: conflicting S = None and lev: cdclW-M-level-inv S
  shows full cdclW S V  $\longleftrightarrow$  full cdclW-merge-restart S V

```

proof

```

  assume full: full cdclW-merge-restart S V
  then have st: cdclW** S V
    using rtranclp-mono[of cdclW-merge-restart cdclW**] cdclW-merge-restart-cdclW
    unfolding full-def by auto

```

```

  have n-s: no-step cdclW-merge-restart V
    using full unfolding full-def by auto
  have n-s-bj: no-step cdclW-bj V
    using rtranclp-cdclW-merge-restart-no-step-cdclW-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 cdclW.conflict cdclW-consistent-inv lev rtranclp-cdclW-consistent-inv st by blast
  then have  $\bigwedge S'. \text{conflict } V S' \implies \text{False}$ 
    using n-s n-s-bj cdclW-bj-exists-normal-form cdclW-merge-restart.simps by meson
  then have n-s-cdclW: no-step cdclW V
    using n-s n-s-bj by (auto simp: cdclW.simps cdclW-o.simps cdclW-merge-restart.simps)
  then show full cdclW S V using st unfolding full-def by auto

```

next

```

  assume full: full cdclW S V
  have no-step cdclW-merge-restart V
    using full no-step-cdclW-no-step-cdclW-merge-restart unfolding full-def by blast

```

moreover

consider

```

  (fw) cdclW-merge-restart** S V and conflicting V = None
  | (bj) T U where
    cdclW-merge-restart** S T and
    conflicting V  $\neq$  None and
    conflict T U and
    cdclW-bj** U V
  using full rtrancl-cdclW-conflicting-true-cdclW-merge-restart confl lev unfolding full-def
  by meson

```

then have $\text{cdcl}_W\text{-merge-restart** } S V$

proof cases

case fw

then show *?thesis* **by fast**

next

case (bj T U)

have $\text{no-step cdcl}_W\text{-bj } V$

using full unfolding full-def by (*meson cdcl_W-o.bj other*)

then have $\text{full cdcl}_W\text{-bj } U V$

using $\langle \text{cdcl}_W\text{-bj** } U V \rangle$ **unfolding full-def by auto**

then have $\text{cdcl}_W\text{-merge-restart } T V$

using $\langle \text{conflict } T U \rangle$ $\text{cdcl}_W\text{-merge-restart.fw-r-conflict}$ **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

19.5 FW with strategy

19.5.1 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' |*
decide': *decide S S' \Longrightarrow no-step cdcl_W-cp S \Longrightarrow full cdcl_W-cp S' S'' \Longrightarrow cdcl_W-s' S S'' |*
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 *rtrancpl-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-rtrancpl-induct*)

case *base*

then show ?case by (metis *cdcl_W-stgy.conflict' full-unfold rtrancpl.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-rtrancplE*)

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-rtrancpl*)

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-rtrancpl-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-rtrancpl*)
by (metis *full1-def rtrancpl-cdcl_W-bj-full1-cdclp-cdcl_W-stgy trancpl-into-rtrancpl*)

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*

$\vee (\exists U' U''. \text{full } cdcl_W\text{-cp } T' U'' \wedge \text{full1 } cdcl_W\text{-bj } U U' \wedge \text{full } cdcl_W\text{-cp } U' U'' \wedge cdcl_W\text{-s}^{**} U U'')$

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 = 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 <cdcl_W-bj⁺⁺ T T''> full1-def step.prem(3)*)

then have *T = U*

proof –

obtain *Z* **where** *cdcl_W-bj T Z*

by (*meson trancpD <cdcl_W-bj⁺⁺ T T''>*)

{ assume *cdcl_W-cp⁺⁺ T U*

then obtain *Z'* **where** *cdcl_W-cp T Z'*

by (*meson trancpD*)

then have *False*

using *<cdcl_W-bj T Z>* **by** (*fastforce simp: cdcl_W-bj.simps cdcl_W-cp.simps*)

}

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 <T = U> <cdcl_W-bj⁺⁺ T T''> 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: $\forall x2. (\exists v3. cdcl_W\text{-cp } x2 v3) = cdcl_W\text{-cp } x2 (ss x2)$

by *moura*

have $\neg cdcl_W\text{-cp } U (ss U)$

by (*meson full full-def*)

then show *?thesis*

using *f1* **by** (*metis (no-types) <T = U> <full1 cdcl_W-bj T T''> bj' calculation(1) r-into-rtrancp*)

qed

ultimately show *?case*

using *<full1 cdcl_W-bj T T''> <full cdcl_W-cp T'' U''> unfolding <T = U>* **by** *blast*

qed


```

lemma cdclW-cp-cdclW-bj-bissimulation':
  assumes
    full cdclW-cp T U and
    cdclW-bj** T T' and
    cdclW-all-struct-inv T and
    no-step cdclW-bj T'
  shows full cdclW-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 = this(1) and bj = this(2) and IH = this(3)[OF this(4,5)] and
    full = this(4) and inv = this(5)
  have cdclW** T T''
    by (metis (no-types, lifting) cdclW-o.bj local.bj mono-rtrancp[of cdclW-bj cdclW T T'] other st
      rtrancp.rtrancp-into-rtrancp)
  then have inv-T'': cdclW-all-struct-inv T''
    using inv rtrancp-cdclW-all-struct-inv-inv by blast
  have cdclW-bj++ T T''
    using local.bj st by auto
  have full1 cdclW-bj T T''
    by (metis <cdclW-bj++ T T''> full1-def step.prem(3))
  then have T = U
  proof –
    obtain Z where cdclW-bj T Z
      by (meson trancpD <cdclW-bj++ T T''>)
    { assume cdclW-cp++ T U
      then obtain Z' where cdclW-cp T Z'
        by (meson trancpD)
      then have False
        using <cdclW-bj T Z> by (fastforce simp: cdclW-bj.simps cdclW-cp.simps)
    }
    then show ?thesis
      using full unfolding full-def rtrancp-unfold by blast
  qed
{ fix U''
  assume full cdclW-cp T'' U''
  moreover then have cdclW-stgy** U U''
    by (metis <T = U> <cdclW-bj++ T T''> rtrancp-cdclW-bj-full1-cdclp-cdclW-stgy rtrancp-unfold)
  moreover have cdclW-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) <T = U> <full1 cdclW-bj T T''> bj' calculation(1)
        r-into-rtrancp)
  }
  qed
ultimately have full1 cdclW-bj U T'' and cdclW-s*** T'' U''

```

```

    using ⟨full1 cdclW-bj T T'⟩ ⟨full cdclW-cp T'' U'⟩ unfolding ⟨T = U⟩
    apply blast
    by (metis ⟨full cdclW-cp T'' U'⟩ cdclW-s'.simps full-unfold rtrancp.simps)
  }
then show ?case
  using ⟨full1 cdclW-bj T T'⟩ full bj' unfolding ⟨T = U⟩ 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
  ∨ (∃ U'. full1 cdclW-bj U U' ∧ (∀ U''. full cdclW-cp U' U'' ⟶ cdclW-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 ⇒ 'st where
    f1: ∀ s sa sb. (¬ full1 cdclW-bj s sa ∨ cdclW-cp s (ss s) ∨ ¬ full cdclW-cp sa sb)
    ∨ cdclW-s' s sb
  using bj' by moura
  have full1 cdclW-bj S T
  by (simp add: cp(2) full1-def local.bj trancp.r-into-trancp)
  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 rtrancpl-unfold
      by (force dest!: trancplD simp:cdclW-bj.simps)
    ultimately show ?thesis using cdclW-s'.bj'[of S U] using fbj by blast
  qed
qed
qed

lemma cdclW-stgy-cdclW-s'-connected':
  assumes cdclW-stgy S U and cdclW-all-struct-inv S
  shows cdclW-s' S U
    ∨ (∃ U' U''. cdclW-s' S U'' ∧ full1 cdclW-bj U U' ∧ full cdclW-cp U' 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 cdclW-all-struct-inv T
      using cdclW-all-struct-inv-inv o other other'.prems by blast
    then obtain T' where T': full cdclW-bj T T'
      using cdclW-bj-exists-normal-form unfolding full-def cdclW-all-struct-inv-def by metis
    then have full cdclW-bj S T'
      proof -
        have f1: cdclW-bj** T T' ∧ no-step cdclW-bj T'
          by (metis (no-types) T' full-def)
        then have cdclW-bj** S T'
          by (meson converse-rtrancpl-into-rtrancpl local.bj)
        then show ?thesis
          using f1 by (simp add: full-def)
      qed
    have cdclW-bj** T T'
      using T' unfolding full-def by simp
    have cdclW-all-struct-inv T
      using cdclW-all-struct-inv-inv o other other'.prems by blast
    then consider
      (T'U) full cdclW-cp T' U
    | (U) U' U'' where
      full cdclW-cp T' U'' and
      full1 cdclW-bj U U' and
      full cdclW-cp U' U'' and
      cdclW-s'* U U''
    using cdclW-cp-cdclW-bj-bissimulation[OF full <cdclW-bj** T T'>] T' unfolding full-def

```

```

    by blast
  then show ?thesis by (metis T' cdclW-s'.simps full-fullI local.bj n-s)
qed
qed

lemma cdclW-stgy-cdclW-s'-no-step:
  assumes cdclW-stgy S U and cdclW-all-struct-inv S and no-step cdclW-bj U
  shows cdclW-s' S U
  using cdclW-stgy-cdclW-s'-connected[OF assms(1,2)] assms(3)
  by (metis (no-types, lifting) full1-def tranclpD)

lemma rtranclp-cdclW-stgy-connected-to-rtranclp-cdclW-s':
  assumes cdclW-stgy** S U and inv: cdclW-M-level-inv S
  shows cdclW-s'** S U  $\vee$  ( $\exists T. cdclW-s'** S T \wedge cdclW-bj^{++} T U \wedge conflicting U \neq None$ )
  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) rtranclp.simps st)
    obtain ssa :: 'st where
      cdclW-cp T ssa
      using conflict' by (metis (no-types) full1-def tranclpD)
    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 rtranclp.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  $\neq$  None
        using IH by blast
      then show ?thesis
        proof cases
          case s'
          moreover

```

```

    have  $cdcl_W$ -M-level-inv  $T$ 
      using  $inv$   $local.step(1)$   $rtrancp$ - $cdcl_W$ -stgy-consistent-inv by  $auto$ 
    then have  $full1$   $cdcl_W$ - $bj$   $T$   $U$ 
      using  $backtrack$ -is- $full1$ - $cdcl_W$ - $bj$   $backtrack$  by  $blast$ 
    then have  $cdcl_W$ - $s'$   $T$   $V$ 
      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  $cdcl_W$ - $cp$   $S'$ 
      using  $bj$ - $T$  by ( $fastforce$   $simp$ :  $cdcl_W$ - $cp$ . $simps$   $cdcl_W$ - $bj$ . $simps$   $dest!$ :  $trancpD$ )
    moreover
      have  $cdcl_W$ -M-level-inv  $T$ 
        using  $inv$   $local.step(1)$   $rtrancp$ - $cdcl_W$ -stgy-consistent-inv by  $auto$ 
      then have  $full1$   $cdcl_W$ - $bj$   $T$   $U$ 
        using  $backtrack$ -is- $full1$ - $cdcl_W$ - $bj$   $backtrack$  by  $blast$ 
      then have  $full1$   $cdcl_W$ - $bj$   $S'$   $U$ 
        using  $bj$ - $T$  unfolding  $full1$ -def by  $fastforce$ 
      ultimately have  $cdcl_W$ - $s'$   $S'$   $V$  using  $full$  by ( $simp$   $add$ :  $bj'$ )
      then show ?thesis using  $S$ - $S'$  by  $auto$ 
    qed
  next
    case  $skip$ 
    then have [ $simp$ ]:  $U = V$ 
      using  $full$   $converse$ - $rtrancpE$  unfolding  $full$ -def by  $fastforce$ 

  consider
    ( $s'$ )  $cdcl_W$ - $s'^{**}$   $S$   $T$ 
    | ( $bj$ )  $S'$  where  $cdcl_W$ - $s'^{**}$   $S$   $S'$  and  $cdcl_W$ - $bj^{++}$   $S'$   $T$  and  $conflicting$   $T \neq None$ 
    using  $IH$  by  $blast$ 
  then show ?thesis
    proof  $cases$ 
      case  $s'$ 
      have  $cdcl_W$ - $bj^{++}$   $T$   $V$ 
        using  $skip$  by  $force$ 
      moreover have  $conflicting$   $V \neq None$ 
        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  $cdcl_W$ - $bj^{++}$   $S'$   $V$ 
        using  $skip$   $bj$ - $T$  by ( $metis$  ( $U = V$ )  $cdcl_W$ - $bj$ . $skip$   $trancp$ . $simps$ )

      moreover have  $conflicting$   $V \neq None$ 
        using  $skip$  by  $auto$ 
      ultimately show ?thesis using  $S$ - $S'$  by  $auto$ 
    qed
  next
    case  $resolve$ 
    then have [ $simp$ ]:  $U = V$ 
      using  $full$   $converse$ - $rtrancpE$  unfolding  $full$ -def by  $fastforce$ 
  consider
    ( $s'$ )  $cdcl_W$ - $s'^{**}$   $S$   $T$ 
    | ( $bj$ )  $S'$  where  $cdcl_W$ - $s'^{**}$   $S$   $S'$  and  $cdcl_W$ - $bj^{++}$   $S'$   $T$  and  $conflicting$   $T \neq None$ 
    using  $IH$  by  $blast$ 

```

```

then show ?thesis
proof cases
case s'
have  $cdcl_W\text{-}bj^{++} \ T \ V$ 
  using resolve by force
moreover have  $conflicting \ V \neq None$ 
  using resolve by auto
ultimately show ?thesis using s' by auto
next
case (bj S') note  $S\text{-}S' = this(1)$  and  $bj\text{-}T = this(2)$ 
have  $cdcl_W\text{-}bj^{++} \ S' \ V$ 
  using resolve bj-T by (metis  $\langle U = V \rangle \ cdcl_W\text{-}bj.resolve \ tranclp.simps$ )
moreover have  $conflicting \ V \neq None$ 
  using resolve by auto
ultimately show ?thesis using S-S' by auto
qed
qed
qed
qed

lemma  $n\text{-step}\text{-}cdcl_W\text{-}stgy\text{-}iff\text{-}no\text{-}step\text{-}cdcl_W\text{-}cl\text{-}cdcl_W\text{-}o$ :
  assumes  $inv: cdcl_W\text{-}all\text{-}struct\text{-}inv \ S$ 
  shows  $no\text{-}step \ cdcl_W\text{-}s' \ S \longleftrightarrow no\text{-}step \ cdcl_W\text{-}cp \ S \wedge no\text{-}step \ cdcl_W\text{-}o \ S$  (is  $?S' \ S \longleftrightarrow ?C \ S \wedge ?O \ S$ )
proof
  assume  $?C \ S \wedge ?O \ S$ 
  then show  $?S' \ S$ 
    by (auto simp:  $cdcl_W\text{-}s'.simps \ full1\text{-}def \ tranclp\text{-}unfold\text{-}begin$ )
next
  assume  $n\text{-}s: ?S' \ S$ 
  have  $?C \ S$ 
  proof (rule ccontr)
    assume  $\neg ?thesis$ 
    then obtain S' where  $cdcl_W\text{-}cp \ S \ S'$ 
      by auto
    then obtain T where  $full1 \ cdcl_W\text{-}cp \ S \ T$ 
      using  $cdcl_W\text{-}cp\text{-}normalized\text{-}element\text{-}all\text{-}inv \ inv$  by (metis (no-types, lifting) full-unfold)
    then show False using n-s  $cdcl_W\text{-}s'.conflict'$  by blast
  qed
  moreover have  $?O \ S$ 
  proof (rule ccontr)
    assume  $\neg ?thesis$ 
    then obtain S' where  $cdcl_W\text{-}o \ S \ S'$ 
      by auto
    then obtain T where  $full1 \ cdcl_W\text{-}cp \ S' \ T$ 
      using  $cdcl_W\text{-}cp\text{-}normalized\text{-}element\text{-}all\text{-}inv \ inv$ 
      by (meson  $cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def \ n\text{-}s \ cdcl_W\text{-}stgy\text{-}cdcl_W\text{-}s'\text{-}connected' \ cdcl_W\text{-}then\text{-}exists\text{-}cdcl_W\text{-}stgy\text{-}step$ )
    then show False using n-s by (meson  $\langle cdcl_W\text{-}o \ S \ S' \rangle \ cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def \ cdcl_W\text{-}stgy\text{-}cdcl_W\text{-}s'\text{-}connected' \ cdcl_W\text{-}then\text{-}exists\text{-}cdcl_W\text{-}stgy\text{-}step \ inv$ )
  qed
  ultimately show  $?C \ S \wedge ?O \ S$  by auto
qed

lemma  $cdcl_W\text{-}s'\text{-}tranclp\text{-}cdcl_W$ :
   $cdcl_W\text{-}s' \ S \ S' \implies cdcl_W^{++} \ S \ S'$ 

```

```

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 cdclW-bj++ Sa S'a ∧ no-step cdclW-bj S'a
  using a2 by (simp add: full1-def)
  then have cdclW-bj Sa (ss S'a Sa cdclW-bj) ∧ cdclW-bj** (ss S'a Sa cdclW-bj) S'a
  using f3 by auto
  then show cdclW++ Sa S''
  using a1 n-s by (meson bj other rtranclp-cdclW-bj-full1-cdclp-cdclW-stgy
    rtranclp-cdclW-stgy-rtranclp-cdclW rtranclp-into-tranclp2)
qed

lemma tranclp-cdclW-s'-tranclp-cdclW:
  cdclW-s'++ S S' ⇒ cdclW++ S S'
  apply (induct rule: tranclp.induct)
  using cdclW-s'-tranclp-cdclW apply blast
  by (meson cdclW-s'-tranclp-cdclW tranclp-trans)

lemma rtranclp-cdclW-s'-rtranclp-cdclW:
  cdclW-s'** S S' ⇒ cdclW** S S'
  using rtranclp-unfold[of cdclW-s' S S'] tranclp-cdclW-s'-tranclp-cdclW[of S S'] by auto

lemma full-cdclW-stgy-iff-full-cdclW-s':
  assumes inv: cdclW-all-struct-inv S
  shows full cdclW-stgy S T ⇔ full cdclW-s' S T (is ?S ⇔ ?S')
proof
  assume ?S'
  then have cdclW** S T
  using rtranclp-cdclW-s'-rtranclp-cdclW[of S T] unfolding full-def by blast
  then have inv': cdclW-all-struct-inv T
  using rtranclp-cdclW-all-struct-inv-inv inv by blast
  have cdclW-stgy** S T
  using ⟨?S'⟩ unfolding full-def
  using cdclW-s'-is-rtranclp-cdclW-stgy rtranclp-mono[of cdclW-s' cdclW-stgy**] by auto
  then show ?S
  using ⟨?S'⟩ inv' cdclW-stgy-cdclW-s'-connected' unfolding full-def by blast
next
  assume ?S
  then have inv-T: cdclW-all-struct-inv T
  by (metis assms full-def rtranclp-cdclW-all-struct-inv-inv rtranclp-cdclW-stgy-rtranclp-cdclW)

consider
  (s') cdclW-s'** S T

```

```

| (st) S' where cdclW-s'** S S' and cdclW-bj++ S' T and conflicting T ≠ None
using rtrancp-cdclW-stgy-connected-to-rtrancp-cdclW-s'[of S T] inv ⟨?S⟩
unfolding full-def cdclW-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 option-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!: trancpD 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-s'** 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-cdclW-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-cdclW-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 *cdcl_W-cp-normalized-element-all-inv* **by** (*meson* *assms*(1) *assms*(2) *cdcl_W-all-struct-inv-inv*
cdcl_W-cp-normalized-element-all-inv *decide* *other*)
then show *?thesis*
by (*metis* *assms* *cdcl_W-cp-normalized-element-all-inv* *cdcl_W-stgy.conflict'* *decide* *full-unfold*
other')
qed

lemma *rtranclp-cdcl_W-cp-conflicting-Some*:
*cdcl_W-cp** S T \implies conflicting S = Some D \implies S = T*
using *rtranclpD* *tranclpD* **by** *fastforce*

inductive *cdcl_W-merge-cp* :: '*st* \Rightarrow '*st* \Rightarrow bool **where**
conflict'[intro]: conflict S T \implies full cdcl_W-bj T U \implies cdcl_W-merge-cp S U |
propagate'[intro]: propagate⁺⁺ S S' \implies cdcl_W-merge-cp S S'

lemma *cdcl_W-merge-restart-cases*[*consumes* 1, *case-names* *conflict* *propagate*]:
assumes
cdcl_W-merge-cp S U and
 $\bigwedge T. \text{conflict } S \ T \implies \text{full } \text{cdcl}_W\text{-bj } T \ U \implies P$ **and**
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-merge-cp S T \implies cdcl_W-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-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*:
full1 cdcl_W-bj S T \implies no-step cdcl_W-cp S
by (*metis* *rtranclp-unfold* *cdcl_W-cp-conflicting-not-empty* *option.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]: full1 cdcl_W-cp S S' \implies cdcl_W-s'-without-decide S S' |
bj'-without-decide[intro]: full1 cdcl_W-bj S S' \implies no-step cdcl_W-cp S \implies full cdcl_W-cp S' S''
 \implies *cdcl_W-s'-without-decide S S''*

lemma *rtranclp-cdcl_W-s'-without-decide-rtranclp-cdcl_W*:
*cdcl_W-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-s'-without-decide** S T \implies cdcl_W-s'*** S T*

```

proof (induction rule: rtrancpl-induct)
  case base
  then show ?case by simp
next
  case (step y z) note a2 = this(2) and a1 = this(3)
  have cdclW-s' y z
    using a2 by (metis (no-types) bj' cdclW-s'.conflict' cdclW-s'-without-decide.cases)
  then show cdclW-sl* 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 = None
  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
next
  case bj-prop note s' = this(1) and bj-T' = this(2) and T''-U = this(3)
  have no-step cdclW-cp T'
    using bj-T' full1-cdclW-bj-no-step-cdclW-bj by blast
  moreover 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 blast
  ultimately have cdclW-s'-without-decide T' U'
    using bj'-without-decide[of T' T'' U'] bj-T' by (simp add: full-unfold)
  then have cdclW-s'-without-decide** S U'
    using s' rtrancpl.intros(2)[of - S T' U'] by blast
  then show ?thesis
    by (metis full-unfold local.bj rtrancpl.rtrancpl-refl)
qed
qed
qed

```

lemma *rtrancpl-cdcl_W-s'-without-decide-is-rtrancpl-cdcl_W-merge-cp:*

```

  assumes
    cdclW-s'-without-decide** S V and
    confl: conflicting S = None
  shows
    (cdclW-merge-cp** S V ∧ conflicting V = None)
    ∨ (cdclW-merge-cp** S V ∧ conflicting V ≠ None ∧ no-step cdclW-cp V ∧ no-step cdclW-bj V)
    ∨ (∃ T. cdclW-merge-cp** S T ∧ conflict T V)
  using assms(1)
proof (induction)
  case base
  then show ?case using confl by auto
next
  case (step U V) note st = this(1) and s = this(2) and IH = this(3)
  from s show ?case
  proof (cases rule: cdclW-s'-without-decide.cases)
    case conflict'-without-decide
    then have rt: cdclW-cp++ U V unfolding full1-def by fast
    then have conflicting U = None
      using trancpl-cdclW-cp-propagate-with-conflict-or-not[of U V]
      conflict by (auto dest!: trancplD simp: rtrancpl-unfold)
    then have cdclW-merge-cp** S U using IH by auto
    consider
      (propa) propagate++ U V
      | (confl') conflict U V
      | (propa-confl') U' where propagate++ U U' conflict U' V
    using trancpl-cdclW-cp-propagate-with-conflict-or-not[OF rt] unfolding rtrancpl-unfold
    by fastforce
  then show ?thesis

```

```

proof cases
  case propa
  then have cdclW-merge-cp U V
    by auto
  moreover have conflicting V = None
    using propa unfolding tranclp-unfold-end by auto
  ultimately show ?thesis using ⟨cdclW-merge-cp** S U⟩ 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 ≠ None
  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 = None
    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 = None)
    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 = None

no-step cdcl_W-s' S

shows *no-step cdcl_W-merge-cp S*

using *assms apply (auto simp: cdcl_W-s'.simps cdcl_W-merge-cp.simps)*

using *conflict-is-full1-cdcl_W-cp apply blast*

using *cdcl_W-cp-normalized-element-all-inv cdcl_W-cp.propagate' by (metis cdcl_W-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 = None and

inv: cdcl_W-M-level-inv S and

n-s: no-step cdcl_W-merge-cp S

shows *no-step cdcl_W-s'-without-decide S*

proof (rule *ccontr*)

assume \neg *no-step cdcl_W-s'-without-decide S*

then obtain *T* **where**

cdcl_W: cdcl_W-s'-without-decide S T

by *auto*

then have *inv-T: cdcl_W-M-level-inv T*

using *rtranclp-cdcl_W-s'-without-decide-rtranclp-cdcl_W[of S T]*

rtranclp-cdcl_W-consistent-inv inv **by** *blast*

from *cdcl_W* **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-cdcl_W-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 cdcl_W-bj T T'*

using *cdcl_W-bj-exists-normal-form inv-T* **by** *blast*

ultimately show *False* **using** *cdcl_W-merge-cp.conflict' n-s* **by** *meson*

next

case (bj'-without-decide *S'*)

then show *?thesis*

using *confl unfolding full1-def* **by** (fastforce *simp: cdcl_W-bj.simps dest: tranclpD*)

qed

qed

lemma *conflicting-true-no-step-s'-without-decide-no-step-cdcl_W-merge-cp*:

assumes

inv: cdcl_W-all-struct-inv S and

n-s: no-step cdcl_W-s'-without-decide S

shows *no-step cdcl_W-merge-cp S*

proof (rule *ccontr*)

assume \neg *?thesis*

```

then obtain  $T$  where  $cdcl_W\text{-merge-cp } S \ T$ 
  by auto
then show False
proof cases
  case ( $conflict' \ S'$ )
    then show False using  $n\text{-s } conflict'\text{-without-decide } conflict\text{-is-full1-cdcl}_W\text{-cp}$  by blast
next
  case  $propagate'$ 
  moreover
    have  $cdcl_W\text{-all-struct-inv } T$ 
      using inv by ( $meson \ local.propagate' \ rtranclp\text{-cdcl}_W\text{-all-struct-inv-inv} \ rtranclp\text{-propagate-is-rtranclp-cdcl}_W \ tranclp\text{-into-rtranclp}$ )
    then obtain  $U$  where  $full \ cdcl_W\text{-cp } T \ U$ 
      using  $cdcl_W\text{-cp-normalized-element-all-inv}$  by auto
    ultimately have  $full1 \ cdcl_W\text{-cp } S \ U$ 
      using  $tranclp\text{-full-full1I}[of \ cdcl_W\text{-cp } S \ T \ U] \ cdcl_W\text{-cp.propagate}' \ tranclp\text{-mono}[of \ propagate \ cdcl_W\text{-cp}]$  by blast
    then show False using  $conflict'\text{-without-decide } n\text{-s}$  by blast
qed
qed

```

lemma $no\text{-step-cdcl}_W\text{-merge-cp-no-step-cdcl}_W\text{-cp}$:
 $no\text{-step } cdcl_W\text{-merge-cp } S \implies cdcl_W\text{-M-level-inv } S \implies no\text{-step } cdcl_W\text{-cp } S$
 using $cdcl_W\text{-bj-exists-normal-form } cdcl_W\text{-consistent-inv}[OF \ cdcl_W.conflict, of \ S]$
 by ($metis \ cdcl_W\text{-cp.cases } cdcl_W\text{-merge-cp.simps } tranclp.intros(1)$)

lemma $conflicting\text{-not-true-rtranclp-cdcl}_W\text{-merge-cp-no-step-cdcl}_W\text{-bj}$:
 assumes
 $conflicting \ S = None$ and
 $cdcl_W\text{-merge-cp}^{**} \ S \ T$
 shows $no\text{-step } cdcl_W\text{-bj } T$
 using $assms(2,1)$ by (*induction*)
 ($fastforce \ simp: \ cdcl_W\text{-merge-cp.simps } full\text{-def } tranclp\text{-unfold-end } cdcl_W\text{-bj.simps}$) +

lemma $conflicting\text{-true-full-cdcl}_W\text{-merge-cp-iff-full-cdcl}_W\text{-s'without-decode}$:
 assumes
 $confl: \ conflicting \ S = None$ and
 $inv: \ cdcl_W\text{-all-struct-inv } S$
 shows
 $full \ cdcl_W\text{-merge-cp } S \ V \longleftrightarrow full \ cdcl_W\text{-s'without-decode } S \ V \text{ (is } ?fw \longleftrightarrow ?s')$

proof
 assume $?fw$
 then have $st: \ cdcl_W\text{-merge-cp}^{**} \ S \ V$ and $n\text{-s}: \ no\text{-step } cdcl_W\text{-merge-cp } V$
 unfolding $full\text{-def}$ by *blast* +
 have $inv\text{-}V: \ cdcl_W\text{-all-struct-inv } V$
 using $rtranclp\text{-cdcl}_W\text{-merge-cp-rtranclp-cdcl}_W[of \ S \ V] \langle ?fw \rangle$ unfolding $full\text{-def}$
 by ($simp \ add: \ inv \ rtranclp\text{-cdcl}_W\text{-all-struct-inv-inv}$)
 consider
 (s') $cdcl_W\text{-s'without-decode}^{**} \ S \ V$
 | ($propa$) T where $cdcl_W\text{-s'without-decode}^{**} \ S \ T$ and $propagate^{++} \ T \ V$
 | (bj) $T \ U$ where $cdcl_W\text{-s'without-decode}^{**} \ S \ T$ and $full1 \ cdcl_W\text{-bj } T \ U$ and $propagate^{**} \ U \ V$
 using $rtranclp\text{-cdcl}_W\text{-merge-cp-is-rtranclp-cdcl}_W\text{-s'without-decode } confl \ st \ n\text{-s}$ by *metis*
 then have $cdcl_W\text{-s'without-decode}^{**} \ S \ V$
 proof cases
 case s'

```

then show ?thesis .
next
case propa note s' = this(1) and propa = this(2)
have no-step 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 full1 cdclW-cp T V
  using propa tranclp-mono[of propagate cdclW-cp] cdclW-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 = None)
case False
{ fix ss :: 'st
  have ff1:  $\forall s sa. \neg cdcl_W-s' s sa \vee full1 cdcl_W-cp s sa$ 
     $\vee (\exists sb. decide s sb \wedge no\_step cdcl_W-cp s \wedge full cdcl_W-cp sb sa)$ 
     $\vee (\exists sb. full1 cdcl_W-bj s sb \wedge no\_step cdcl_W-cp s \wedge full cdcl_W-cp sb sa)$ 
    by (metis cdclW-s'.cases)
  have ff2:  $(\forall p s sa. \neg full1 p (s::'st) sa \vee p^{++} s sa \wedge no\_step p sa)$ 
     $\wedge (\forall p s sa. (\neg p^{++} (s::'st) sa \vee (\exists s. p sa s)) \vee full1 p s sa)$ 
    by (meson full1-def)
  obtain ssa :: ('st  $\Rightarrow$  'st  $\Rightarrow$  bool)  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  'st where
    ff3:  $\forall p s sa. \neg p^{++} s sa \vee p s (ssa p s sa) \wedge p^{**} (ssa p s sa) sa$ 
    by (metis (no-types) tranclpD)
  then have a3:  $\neg cdcl_W-cp^{++} V ss$ 
    using False by (metis option-full-cdclW-cp full-def)
  have  $\bigwedge s. \neg cdcl_W-bj^{++} V s$ 
    using ff3 False by (metis confl st
      conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj)
  then have  $\neg cdcl_W-s'-without-decide V ss$ 
    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 $st: cdcl_W-s'-without-decide^{**} S V$ and $n-s: no-step cdcl_W-s'-without-decide V$
 unfolding full-def by auto
 then have $cdcl_W^{**} S V$
 using $rtranclp-cdcl_W-s'-without-decide-rtranclp-cdcl_W st$ 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 $tranclp-mono[of cdcl_W-bj cdcl_W] cdcl_W.other cdcl_W-o.bj$ unfolding full1-def by blast
 then have $cdcl_W-all-struct-inv W'$
 by (meson $inv-V rtranclp-cdcl_W-all-struct-inv-inv tranclp-into-rtranclp$)
 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 $conflicting V = None$
 | ($cp-false$) $cdcl_W-merge-cp^{**} S V$ and $conflicting V \neq None$ and $no-step cdcl_W-cp V$ and
 $no-step cdcl_W-bj V$
 | ($cp-conf$) 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 meson
 then have $cdcl_W-merge-cp^{**} S V$
 proof cases
 case $cp-conf$ 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 = None* and

inv: *cdcl_W-all-struct-inv S*

shows

full1 cdcl_W-merge-cp S V \longleftrightarrow *full1 cdcl_W-s'-without-decide S V*

proof –

have *full cdcl_W-merge-cp S V = full cdcl_W-s'-without-decide S V*

using *confl conflicting-true-full-cdcl_W-merge-cp-iff-full-cdcl_W-s'-without-decode inv*

by *blast*

then show ?thesis unfolding *full-unfold full1-def*

by (*metis (mono-tags) tranclp-unfold-begin*)

qed

lemma *conflicting-true-full1-cdcl_W-merge-cp-imp-full1-cdcl_W-s'-without-decode:*

assumes

fw: *full1 cdcl_W-merge-cp S V* and

inv: *cdcl_W-all-struct-inv S*

shows

full1 cdcl_W-s'-without-decide S V

proof –

have *conflicting S = None*

using *fw unfolding full1-def* by (*auto dest!: tranclpD simp: cdcl_W-merge-cp.simps*)

then show ?thesis

using *conflicting-true-full1-cdcl_W-merge-cp-iff-full1-cdcl_W-s'-without-decode fw inv* by *blast*

qed

inductive *cdcl_W-merge-stgy* **where**

fw-s-cp[intro]: *full1 cdcl_W-merge-cp S T* \implies *cdcl_W-merge-stgy S T* |

fw-s-decide[intro]: *decide S T* \implies *no-step cdcl_W-merge-cp S* \implies *full cdcl_W-merge-cp T U*

\implies *cdcl_W-merge-stgy S U*

lemma *cdcl_W-merge-stgy-tranclp-cdcl_W-merge:*

assumes *fw*: *cdcl_W-merge-stgy S T*

shows *cdcl_W-merge⁺⁺ S T*

proof –

{ **fix** *S T*

assume *full1 cdcl_W-merge-cp S T*

then have *cdcl_W-merge⁺⁺ S T*

using *tranclp-mono[of cdcl_W-merge-cp cdcl_W-merge⁺⁺] cdcl_W-merge-cp-tranclp-cdcl_W-merge*

unfolding *full1-def*

by *auto*

} **note** *full1-cdcl_W-merge-cp-cdcl_W-merge = this*

show ?thesis

using *fw*

apply (*induction rule: cdcl_W-merge-stgy.induct*)

using *full1-cdcl_W-merge-cp-cdcl_W-merge* **apply** *simp*

unfolding *full-unfold* by (*auto dest!: full1-cdcl_W-merge-cp-cdcl_W-merge fw-decide*)

qed

lemma *rtranclp-cdcl_W-merge-stgy-rtranclp-cdcl_W-merge*:
assumes *fw*: *cdcl_W-merge-stgy*** *S T*
shows *cdcl_W-merge*** *S T*
using *fw cdcl_W-merge-stgy-tranclp-cdcl_W-merge rtranclp-mono*[*of cdcl_W-merge-stgy cdcl_W-merge⁺⁺*]
unfolding *tranclp-rtranclp-rtranclp* **by** *blast*

lemma *cdcl_W-merge-stgy-rtranclp-cdcl_W*:
*cdcl_W-merge-stgy S T \implies cdcl_W** S T*
apply (*induction rule*: *cdcl_W-merge-stgy.induct*)
using *rtranclp-cdcl_W-merge-cp-rtranclp-cdcl_W* **unfolding** *full1-def*
apply (*simp add*: *tranclp-into-rtranclp*)
using *rtranclp-cdcl_W-merge-cp-rtranclp-cdcl_W cdcl_W-o.decide cdcl_W.other* **unfolding** *full-def*
by (*meson r-into-rtranclp rtranclp-trans*)

lemma *rtranclp-cdcl_W-merge-stgy-rtranclp-cdcl_W*:
*cdcl_W-merge-stgy** S T \implies cdcl_W** S T*
using *rtranclp-mono*[*of cdcl_W-merge-stgy cdcl_W***] *cdcl_W-merge-stgy-rtranclp-cdcl_W* **by** *auto*

lemma *cdcl_W-merge-stgy-cases*[*consumes 1, case-names fw-s-cp fw-s-decide*]:
assumes
cdcl_W-merge-stgy S U
full1 cdcl_W-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-merge-stgy.simps*)

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''*
 $\implies cdcl_W\text{-s'-w } S \ S''$

lemma *cdcl_W-s'-w-rtranclp-cdcl_W*:
*cdcl_W-s'-w S T \implies cdcl_W** S T*
apply (*induction rule*: *cdcl_W-s'-w.induct*)
using *rtranclp-cdcl_W-s'-without-decide-rtranclp-cdcl_W* **unfolding** *full1-def*
apply (*simp add*: *tranclp-into-rtranclp*)
using *rtranclp-cdcl_W-s'-without-decide-rtranclp-cdcl_W* **unfolding** *full-def*
by (*meson decide other rtranclp-into-tranclp2 tranclp-into-rtranclp*)

lemma *rtranclp-cdcl_W-s'-w-rtranclp-cdcl_W*:
*cdcl_W-s'-w** S T \implies cdcl_W** S T*
using *rtranclp-mono*[*of cdcl_W-s'-w cdcl_W***] *cdcl_W-s'-w-rtranclp-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 = None* **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 tranclpD*
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 = None*
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 tranclpD*)

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 rtrancpl-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 $S \rightarrow T$: cdcl_W-bj S T
 by auto
 have cdcl_W-all-struct-inv T
 using $S \rightarrow T$ cdcl_W-all-struct-inv-inv inv other by blast
 then obtain T' where full1 cdcl_W-bj S T'
 using cdcl_W-bj-exists-normal-form[of T] full-full1 $S \rightarrow T$ unfolding cdcl_W-all-struct-inv-def
 by metis
 moreover
 then have cdcl_W** S T'
 using rtrancpl-mono[of cdcl_W-bj cdcl_W] cdcl_W.other cdcl_W-o.bj trancpl-into-rtrancpl[of cdcl_W-bj]
 unfolding full1-def by (metis (full-types) predicate2D predicate2I)
 then have cdcl_W-all-struct-inv T'
 using inv rtrancpl-cdcl_W-all-struct-inv-inv by blast
 then obtain U where full cdcl_W-cp T' U
 using cdcl_W-cp-normalized-element-all-inv by blast
 moreover have no-step cdcl_W-cp S
 using $S \rightarrow T$ by (auto simp: cdcl_W-bj.simps)
 ultimately show False
 using assms cdcl_W-s'-without-decide.intros(2)[of S T' U] by fast
 qed

lemma cdcl_W-s'-w-no-step-cdcl_W-bj:
 assumes cdcl_W-s'-w S T and cdcl_W-all-struct-inv S
 shows no-step cdcl_W-bj T
 using assms apply induction
 using rtrancpl-cdcl_W-s'-without-decide-rtrancpl-cdcl_W rtrancpl-cdcl_W-all-struct-inv-inv
 no-step-cdcl_W-s'-without-decide-no-step-cdcl_W-bj unfolding full1-def
 apply (meson trancpl-into-rtrancpl)
 using rtrancpl-cdcl_W-s'-without-decide-rtrancpl-cdcl_W rtrancpl-cdcl_W-all-struct-inv-inv
 no-step-cdcl_W-s'-without-decide-no-step-cdcl_W-bj unfolding full-def
 by (meson cdcl_W-merge-restart-cdcl_W fw-r-decide)

lemma rtrancpl-cdcl_W-s'-w-no-step-cdcl_W-bj-or-eq:
 assumes cdcl_W-s'-w** S T and cdcl_W-all-struct-inv S
 shows $S = T \vee$ no-step cdcl_W-bj T
 using assms apply induction
 apply simp
 using rtrancpl-cdcl_W-s'-w-rtrancpl-cdcl_W rtrancpl-cdcl_W-all-struct-inv-inv
 cdcl_W-s'-w-no-step-cdcl_W-bj by meson

lemma rtrancpl-cdcl_W-s'-no-step-cdcl_W-s'-without-decide-decomp-into-cdcl_W-merge:
 assumes

```

     $cdcl_W\text{-}s'^{**} R V$  and
     $conflicting R = None$  and
     $inv: cdcl_W\text{-}all\text{-}struct\text{-}inv R$ 
shows ( $cdcl_W\text{-}merge\text{-}stgy^{**} R V \wedge conflicting V = None$ )
 $\vee (cdcl_W\text{-}merge\text{-}stgy^{**} R V \wedge conflicting V \neq None \wedge no\text{-}step\ cdcl_W\text{-}bj V)$ 
 $\vee (\exists S T U. cdcl_W\text{-}merge\text{-}stgy^{**} R S \wedge no\text{-}step\ cdcl_W\text{-}merge\text{-}cp S \wedge decide S T$ 
 $\wedge cdcl_W\text{-}merge\text{-}cp^{**} T U \wedge conflict U V)$ 
 $\vee (\exists S T. cdcl_W\text{-}merge\text{-}stgy^{**} R S \wedge no\text{-}step\ cdcl_W\text{-}merge\text{-}cp S \wedge decide S T$ 
 $\wedge cdcl_W\text{-}merge\text{-}cp^{**} T V$ 
 $\wedge conflicting V = None)$ 
 $\vee (cdcl_W\text{-}merge\text{-}cp^{**} R V \wedge conflicting V = None)$ 
 $\vee (\exists U. cdcl_W\text{-}merge\text{-}cp^{**} R U \wedge conflict U V)$ 
using  $assms(1,2)$ 
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
 $n\text{-}s\text{-}R = this(4)$ 
  from  $s'$ 
  show ?case
  proof cases
    case conflict'
    consider
      ( $s'$ )  $cdcl_W\text{-}merge\text{-}stgy^{**} R V$ 
      | ( $dec\text{-}confl$ )  $S T U$  where  $cdcl_W\text{-}merge\text{-}stgy^{**} R S$  and  $no\text{-}step\ cdcl_W\text{-}merge\text{-}cp S$  and
 $decide S T$  and  $cdcl_W\text{-}merge\text{-}cp^{**} T U$  and  $conflict U V$ 
      | ( $dec$ )  $S T$  where  $cdcl_W\text{-}merge\text{-}stgy^{**} R S$  and  $no\text{-}step\ cdcl_W\text{-}merge\text{-}cp S$  and  $decide S T$ 
and  $cdcl_W\text{-}merge\text{-}cp^{**} T V$  and  $conflicting V = None$ 
      | ( $cp$ )  $cdcl_W\text{-}merge\text{-}cp^{**} R V$ 
      | ( $cp\text{-}confl$ )  $U$  where  $cdcl_W\text{-}merge\text{-}cp^{**} R U$  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
 $rtranclp\text{-}cdcl_W\text{-}merge\text{-}stgy'\text{-}no\text{-}step\text{-}cdcl_W\text{-}cp\text{-}or\text{-}eq$ )
      consider
        ( $V\text{-}W$ )  $V = W$ 
        | (propa)  $propagate^{++} V W$  and  $conflicting W = None$ 
        | (propa-confl)  $V'$  where  $propagate^{**} V V'$  and  $conflict V' W$ 
        using  $tranclp\text{-}cdcl_W\text{-}cp\text{-}propagate\text{-}with\text{-}conflict\text{-}or\text{-}not[of\ V\ W]\ conflict'$ 
        unfolding  $full\text{-}unfold\ full1\text{-}def$  by meson
      then show ?thesis
      proof cases
        case  $V\text{-}W$ 
        then show ?thesis using  $\langle R = V \rangle n\text{-}s\text{-}R$  by simp
      next
      case propa
      then show ?thesis using  $\langle R = V \rangle$  by auto
      next
      case propa-confl
      moreover

```

```

      then have  $cdcl_W\text{-merge-cp}^{**} V V'$ 
      by (metis  $rtranclp\text{-unfold } cdcl_W\text{-merge-cp.propagate' } r\text{-into-rtranclp}$ )
      ultimately show ?thesis using  $s' \langle R = V \rangle$  by blast
    qed
  next
    case  $dec\text{-confl}$  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  $conflicting W = None$ 
    | (propa-confl)  $V'$  where  $propagate^{**} V V'$  and  $conflict V' W$ 
    using  $tranclp\text{-}cdcl_W\text{-cp-propagate-with-conflict-or-not}[of V W] conflict'$ 
    unfolding full1-def by meson
    then show ?thesis
    proof cases
      case propa
      then show ?thesis
      by (meson  $T-V cdcl_W\text{-merge-cp.propagate' } dec rtranclp.rtrancl\text{-into-rtrancl}$ )
    next
      case  $propa\text{-confl}$ 
      then have  $cdcl_W\text{-merge-cp}^{**} T V'$ 
      using  $T-V$  by (metis  $rtranclp\text{-unfold } cdcl_W\text{-merge-cp.propagate' } rtranclp.simps$ )
      then show ?thesis using  $dec propa\text{-confl}(2)$  by metis
    qed
  next
    case  $cp$ 
    consider
      (propa)  $propagate^{++} V W$  and  $conflicting W = None$ 
    | (propa-confl)  $V'$  where  $propagate^{**} V V'$  and  $conflict V' W$ 
    using  $tranclp\text{-}cdcl_W\text{-cp-propagate-with-conflict-or-not}[of V W] conflict'$ 
    unfolding full1-def by meson
    then show ?thesis
    proof cases
      case propa
      then show ?thesis by (meson  $cdcl_W\text{-merge-cp.propagate' } cp rtranclp.rtrancl\text{-into-rtrancl}$ )
    next
      case  $propa\text{-confl}$ 
      then show ?thesis
      using  $propa\text{-confl}(2)$  by (metis  $rtranclp\text{-unfold } cdcl_W\text{-merge-cp.propagate' } cp rtranclp.rtrancl\text{-into-rtrancl}$ )
    qed
  next
    case  $cp\text{-confl}$ 
    then show ?thesis using  $conflict'$  unfolding full1-def by (fastforce dest!:  $tranclpD$ )
  qed
next
case (decide'  $V'$ )
then have  $conf\text{-}V$ :  $conflicting V = None$ 
by auto
consider
  ( $s'$ )  $cdcl_W\text{-merge-stgy}^{**} R V$ 
| ( $dec\text{-confl}$ )  $S T U$  where  $cdcl_W\text{-merge-stgy}^{**} R S$  and no-step  $cdcl_W\text{-merge-cp } S$  and
  decide  $S T$  and  $cdcl_W\text{-merge-cp}^{**} T U$  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 = None
| (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 confl-V': conflicting V' = None using decide'(1) by auto
  have full: full1 cdclW-cp V' W ∨ (V' = W ∧ 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 = None
  | (propa-conf) V'' where propagate** V' V'' and conflict V'' W
  using tranclp-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[of V] by blast
    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-conf
    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-conf(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 = None
  | (propa-conf) 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 meson

```

```

then show ?thesis
proof cases
  case V'-W
  moreover have conflicting V' = None
    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-rtrancpl)
next
  case propa-confl
  moreover then have cdclW-merge-cp** V' V''
    by (metis cdclW-merge-cp.propagate' rtrancpl-unfold trancpl-unfold-end)
  ultimately show ?thesis using ⟨cdclW-merge-stgy** R V⟩ decide'
    ⟨no-step cdclW-merge-cp V⟩ by (meson r-into-rtrancpl)
qed
next
  case cp
  have no-step cdclW-merge-cp V
    using conf-V local.decide'(2) no-step-cdclW-cp-no-step-cdclW-merge-restart by blast
  then have full cdclW-merge-cp R V
    unfolding full-def using cp by fast
  then have cdclW-merge-stgy** R V
    unfolding full-unfold by auto
  have full1 cdclW-cp V' W ∨ (V' = W ∧ 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 = None
  | (propa-confl) V'' where propagate** V' V'' and conflict V'' W
  using trancpl-cdclW-cp-propagate-with-conflict-or-not[of V' W] decide'
  unfolding full-unfold full1-def by meson
then show ?thesis

proof cases
  case V'-W
  moreover have conflicting V' = None
    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-rtrancpl)
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 using ⟨cdclW-merge-stgy** R V⟩ decide'
      ⟨no-step cdclW-merge-cp V⟩ by (meson r-into-rtrancp)
  qed
next
  case (dec-conf)
  show ?thesis using conf-V dec-conf(5) by auto
next
  case cp-conf
  then show ?thesis using decide' apply - by (intro HOL.disjI2) fastforce
qed
next
case (bj' V')
then have ¬no-step cdclW-bj V
  by (auto dest: trancpD simp: full1-def)
then consider
  (s') cdclW-merge-stgy** R V and conflicting V = None
| (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 = None
| (cp) cdclW-merge-cp** R V and conflicting V = None
| (cp-conf) 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!: trancpD 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!: trancpD simp: cdclW-bj.simps)
  then show ?thesis by fast
next
  case dec-conf
  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-conf(4) by simp
  consider
    (V'-W) V' = W
  | (propa) propagate++ V' W and conflicting W = None
  | (propa-conf) V'' where propagate** V' V'' and conflict V'' W
  using trancp-cdclW-cp-propagate-with-conflict-or-not[of V' W] bj'(3)
  unfolding full-unfold full1-def by meson
  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 trancpD
      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 = None
  then show ?thesis using ⟨cdclW-merge-stgy** R V'⟩ ⟨V' = W⟩ by auto
next
  assume conflicting W ≠ None
  then show ?thesis
    using ⟨cdclW-merge-stgy** R V'⟩ ⟨V' = W⟩ by (metis ⟨cdclW-merge-cp U V'⟩
      conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj dec-confl(5)
      r-into-rtranclp 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)
    rtranclp.rtrancl-into-rtrancl)
next
  case propa-confl
  moreover then have cdclW-merge-cp** V' V''
    by (metis cdclW-merge-cp.propagate' rtranclp-unfold tranclp-unfold-end)
  ultimately show ?thesis by (meson ⟨cdclW-merge-cp** T V'⟩ dec-confl(1-3) rtranclp-trans)
qed
next
  case cp note - = this(2)
  then show ?thesis using bj'(1) ⟨¬ no-step cdclW-bj V'⟩
    conflicting-not-true-rtranclp-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 = None
  | (propa-confl) V'' where propagate** V' V'' and conflict V'' W
  using tranclp-cdclW-cp-propagate-with-conflict-or-not[of V' W] bj'
  unfolding full-unfold full1-def by meson
  then show ?thesis

proof cases
  case V'-W
  show ?thesis
  proof cases
    assume conflicting V' = None
    then show ?thesis
      using V'-W ⟨cdclW-merge-cp U V'⟩ cp-confl(1) by force
  next

```

```

    assume confl: conflicting  $V' \neq \text{None}$ 
    then have no-step cdclW-merge-stgy  $V'$ 
      by (fastforce simp: cdclW-merge-stgy.simps full1-def full-def
          cdclW-merge-cp.simps dest!: tranclpD)
    have no-step cdclW-merge-cp  $V'$ 
      using confl by (auto simp: full1-def full-def cdclW-merge-cp.simps
          dest!: tranclpD)
    moreover have cdclW-merge-cp  $U\ W$ 
      using  $V'-W \langle \text{cdcl}_W\text{-merge-cp } U\ V' \rangle$  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  $\langle \text{no-step cdcl}_W\text{-merge-cp } V' \rangle$  by (auto simp: cdclW-merge-stgy.simps
          full1-def dest!: tranclpD)
    ultimately have cdclW-merge-stgy**  $R\ V'$  by auto
    show ?thesis by (metis  $V'-W \langle \text{cdcl}_W\text{-merge-cp } U\ V' \rangle \langle \text{cdcl}_W\text{-merge-stgy** } R\ V' \rangle$ 
        conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj cp-confl(1)
        rtranclp.rtrancl-into-rtrancl step.premis)
  qed
next
  case propa
  moreover then have cdclW-merge-cp  $V'\ W$ 
    by auto
  ultimately show ?thesis using  $\langle \text{cdcl}_W\text{-merge-cp } U\ V' \rangle$  cp-confl(1) by force
next
  case propa-confl
  moreover then have cdclW-merge-cp**  $V'\ V''$ 
    by (metis cdclW-merge-cp.propagate' rtranclp-unfold tranclp-unfold-end)
  ultimately show ?thesis
    using  $\langle \text{cdcl}_W\text{-merge-cp } U\ V' \rangle$  cp-confl(1) by (metis rtranclp.rtrancl-into-rtrancl
        rtranclp-trans)
  qed
qed
qed
qed

```

lemma *decide-rtranclp-cdcl_W-s'-rtranclp-cdcl_W-s'*:

```

  assumes
    dec: decide  $S\ T$  and
    cdclW-s'l**  $T\ U$  and
    n-s-S: no-step cdclW-cp  $S$  and
    no-step cdclW-cp  $U$ 
  shows cdclW-s'l**  $S\ U$ 
  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

```

```

    ( $TU$ )  $T = U$ 
    | ( $s'-st$ )  $T'$  where cdclW-s'  $T\ T'$  and cdclW-s'l**  $T'\ U$ 
    using st[unfolded rtranclp-unfold] by (auto dest!: tranclpD)

```

then show ?case

proof *cases*

```

  case  $TU$ 

```

```

then show ?thesis
proof -
  assume a1:  $T = U$ 
  then have f2:  $cdcl_W-s' T V$ 
    using  $s'$  by force
  obtain  $ss :: 'st$  where
     $cdcl_W-s^{**} S T \vee cdcl_W-cp T ss$ 
  using a1 step.IH by blast
  then show ?thesis
    using f2 by (metis (full-types)  $cdcl_W-s'.decide'$   $cdcl_W-s'E$  dec full1-is-full  $n-s-S$ 
      rtrancpl-unfold trancpl-unfold-end)
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!: trancplD 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 rtrancpl-cdcl_W-merge-stgy-rtrancpl-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  $cdcl_W-all-struct-inv S$ 

```

```

using inv rtranclp-cdclW-all-struct-inv-inv rtranclp-cdclW-merge-stgy-rtranclp-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 tranclp-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 rtranclp-unfold st
        tranclp-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
        rtranclp-cdclW-s'-without-decide-rtranclp-cdclW-s' rtranclp-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' = None
  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
    rtranclp-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) rtranclp-cdclW-s'-without-decide-rtranclp-cdclW-s')
  have cdclW-merge-stgy** S T
  using fw by blast
  then have cdclW-s*** S T
  using decide-rtranclp-cdclW-s'-rtranclp-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
    rtranclp-cdclW-merge-stgy'-no-step-cdclW-cp-or-eq)
  then show ?thesis using IH by auto
  qed
qed

```

lemma *rtranclp-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 *rtrancp-cdcl_W-stgy-distinct-mset-clauses*[*OF invR - dist R*]
invR st *rtrancp-mono*[*of cdcl_W-s' cdcl_W-stgy***] *cdcl_W-s'-is-rtrancp-cdcl_W-stgy*
by (*auto dest!*: *cdcl_W-s'-is-rtrancp-cdcl_W-stgy* *rtrancp-cdcl_W-merge-stgy-rtrancp-cdcl_W-s'*)

lemma *no-step-cdcl_W-s'-no-step-cdcl_W-merge-stgy*:

assumes

inv: *cdcl_W-all-struct-inv R* **and** *s'*: *no-step cdcl_W-s' R*

shows *no-step cdcl_W-merge-stgy R*

proof –

{ fix *ss* :: '*st*
obtain *ssa* :: '*st* ⇒ '*st* ⇒ '*st* **where**
ff1: $\bigwedge s \text{ sa. } \neg \text{cdcl}_W\text{-merge-stgy } s \text{ sa} \vee \text{full1 } \text{cdcl}_W\text{-merge-cp } s \text{ sa} \vee \text{decide } s \text{ (ssa } s \text{ sa)}$
using *cdcl_W-merge-stgy.cases* **by** *moura*
obtain *ssb* :: ('*st* ⇒ '*st* ⇒ *bool*) ⇒ '*st* ⇒ '*st* ⇒ '*st* **where**
ff2: $\bigwedge p \text{ s sa. } \neg p^{++} \text{ s sa} \vee p \text{ s (ssb } p \text{ s sa)}$
by (*meson trancp-unfold-begin*)
obtain *ssc* :: '*st* ⇒ '*st* **where**
ff3: $\bigwedge s \text{ sa sb. } (\neg \text{cdcl}_W\text{-all-struct-inv } s \vee \neg \text{cdcl}_W\text{-cp } s \text{ sa} \vee \text{cdcl}_W\text{-s' } s \text{ (ssc } s))$
 $\wedge (\neg \text{cdcl}_W\text{-all-struct-inv } s \vee \neg \text{cdcl}_W\text{-o } s \text{ sb} \vee \text{cdcl}_W\text{-s' } s \text{ (ssc } s))$
using *n-step-cdcl_W-stgy-iff-no-step-cdcl_W-cl-cdcl_W-o* **by** *moura*
then have *ff4*: $\bigwedge s. \neg \text{cdcl}_W\text{-o } R \text{ s}$
using *s' inv* **by** *blast*
have *ff5*: $\bigwedge s. \neg \text{cdcl}_W\text{-cp}^{++} \text{ R } s$
using *ff3 ff2 s'* **by** (*metis inv*)
have $\bigwedge s. \neg \text{cdcl}_W\text{-bj}^{++} \text{ R } s$
using *ff4 ff2* **by** (*metis bj*)
then have $\bigwedge s. \neg \text{cdcl}_W\text{-s'-without-decide } R \text{ s}$
using *ff5* **by** (*simp add: cdcl_W-s'-without-decide.simps full1-def*)
then have $\neg \text{cdcl}_W\text{-s'-without-decide}^{++} \text{ R } ss$
using *ff2* **by** *blast*
then have $\neg \text{cdcl}_W\text{-merge-stgy } R \text{ ss}$
using *ff4 ff1* **by** (*metis (full-types) decide full1-def inv*
conflicting-true-full1-cdcl_W-merge-cp-imp-full1-cdcl_W-s'-without-decode) }
then show *?thesis*
by *fastforce*

qed

lemma *wf-cdcl_W-merge-cp*:

wf{(*T*, *S*). *cdcl_W-all-struct-inv S* ∧ *cdcl_W-merge-cp S T*}

using *wf-trancp-cdcl_W-merge* **by** (*rule wf-subset*) (*auto simp: cdcl_W-merge-cp-trancp-cdcl_W-merge*)

lemma *wf-cdcl_W-merge-stgy*:

wf{(*T*, *S*). *cdcl_W-all-struct-inv S* ∧ *cdcl_W-merge-stgy S T*}

using *wf-trancp-cdcl_W-merge* **by** (*rule wf-subset*)

(*auto simp add: cdcl_W-merge-stgy-trancp-cdcl_W-merge*)

lemma *cdcl_W-merge-cp-obtain-normal-form*:

assumes *inv*: *cdcl_W-all-struct-inv R*

obtains *S* **where** *full cdcl_W-merge-cp R S*

proof –

obtain *S* **where** *full* ($\lambda S \text{ T. } \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-cp } S \text{ T}$) *R S*

using *wf-exists-normal-form-full*[*OF wf-cdcl_W-merge-cp*] **by** *blast*

then have

st: ($\lambda S \text{ T. } \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-cp } S \text{ T}$)^{**} *R S* **and**

n-s: *no-step* ($\lambda S \text{ T. } \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-cp } S \text{ T}$) *S*

```

  unfolding full-def by blast+
have cdclW-merge-cp** R S
  using st by induction auto
moreover
  have cdclW-all-struct-inv S
    using st inv
    apply (induction rule: rtrancp-induct)
    apply simp
    by (meson r-into-rtrancp rtrancp-cdclW-all-struct-inv-inv
        rtrancp-cdclW-merge-cp-rtrancp-cdclW)
  then have no-step cdclW-merge-cp S
    using n-s by auto
ultimately show ?thesis
  using that unfolding full-def by blast
qed

```

lemma no-step-cdcl_W-merge-stgy-no-step-cdcl_W-s':

```

assumes
  inv: cdclW-all-struct-inv R and
  confl: conflicting R = None and
  n-s: no-step cdclW-merge-stgy R
shows no-step cdclW-s' R
proof (rule ccontr)
  assume ¬ ?thesis
  then obtain S where cdclW-s' R S by auto
  then show False
    proof cases
      case conflict'
      then obtain S' where full1 cdclW-merge-cp R S'
        by (metis (full-types) cdclW-merge-cp-obtain-normal-form cdclW-s'-without-decide.simps confl
            conflicting-true-no-step-cdclW-merge-cp-no-step-s'-without-decide full-def full-unfold inv
            cdclW-all-struct-inv-def)
      then show False using n-s by blast
    next
      case (decide' R')
      then have cdclW-all-struct-inv R'
        using inv cdclW-all-struct-inv-inv cdclW.other cdclW-o.decide by meson
      then obtain R'' where full cdclW-merge-cp R' R''
        using cdclW-merge-cp-obtain-normal-form by blast
      moreover have no-step cdclW-merge-cp R
        by (simp add: confl local.decide'(2) no-step-cdclW-cp-no-step-cdclW-merge-restart)
      ultimately show False using n-s cdclW-merge-stgy.intros local.decide'(1) by blast
    next
      case (bj' R')
      then show False
        using confl no-step-cdclW-cp-no-step-cdclW-s'-without-decide inv
        unfolding cdclW-all-struct-inv-def by blast
    qed
  qed
qed

```

lemma rtrancp-cdcl_W-merge-cp-no-step-cdcl_W-bj:

```

assumes conflicting R = None and cdclW-merge-cp** R S
shows no-step cdclW-bj S
using assms conflicting-not-true-rtrancp-cdclW-merge-cp-no-step-cdclW-bj by blast

```

```

lemma rtrancp-cdclW-merge-stgy-no-step-cdclW-bj:
  assumes confl: conflicting R = None 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 = None
    using fw apply cases
    by (auto simp: full1-def cdclW-merge-cp.simps dest!: trancpD)
from fw show ?case
  proof cases
    case fw-s-cp
    then show ?thesis
      using rtrancp-cdclW-merge-cp-no-step-cdclW-bj confl-S
      by (simp add: full1-def trancp-into-rtrancp)
  next
    case (fw-s-decide S')
    moreover then have conflicting S' = None by auto
    ultimately show ?thesis
      using conflicting-not-true-rtrancp-cdclW-merge-cp-no-step-cdclW-bj
      unfolding full-def by meson
  qed
qed

lemma full-cdclW-s'-full-cdclW-merge-restart:
  assumes
    conflicting R = None 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  $\langle \text{cdcl}_W\text{-s}'^{**} R V \rangle$  inv rtrancp-cdclW-all-struct-inv-inv rtrancp-cdclW-s'-rtrancp-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  $\langle \text{full cdcl}_W\text{-s}' R V \rangle$  full-def)
  have n-s-bj: no-step cdclW-bj V
    by (metis  $\langle \text{cdcl}_W\text{-all-struct-inv } V \rangle$   $\langle \text{full cdcl}_W\text{-s}' R V \rangle$  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:  $\forall s. \neg \text{cdcl}_W\text{-all-struct-inv } s \vee \text{cdcl}_W\text{-s}'\text{-without-decide } s \text{ (ssa } s)$ 
         $\vee \text{no-step cdcl}_W\text{-merge-cp } s$ 
        using conflicting-true-no-step-s'-without-decide-no-step-cdclW-merge-cp by moura
        have  $(\forall p \ s \ sa. \neg \text{full } p \ (s::'st) \ sa \vee p^{**} \ s \ sa \wedge \text{no-step } p \ sa)$  and
           $(\forall p \ s \ sa. (\neg p^{**} \ (s::'st) \ sa \vee (\exists s. p \ sa \ s)) \vee \text{full } p \ s \ sa)$ 
          by (meson full-def)+
        then have  $\neg \text{cdcl}_W\text{-merge-cp } V \ ss$ 

```



```

    using ff1 by (metis (no-types) ⟨cdclW-all-struct-inv V⟩ ⟨full cdclW-s' R V⟩ 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 = None
| (fw-confl) cdclW-merge-stgy** R V and conflicting V ≠ None 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 = None
| (cp-no-confl) cdclW-merge-cp** R V and conflicting V = None
| (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
  ⟨cdclW-s'** R V⟩ 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 ⟨decide S T⟩ ⟨no-step cdclW-merge-cp S⟩ by auto
    then show ?thesis using n-s ⟨cdclW-merge-stgy** R S⟩ 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 ⟨decide S T⟩ ⟨no-step cdclW-merge-cp S⟩ by auto
    then show ?thesis using n-s ⟨cdclW-merge-stgy** R S⟩ 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 ∨ 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  $rtrancp\text{-}mono[of\ cdcl_W\text{-}merge\text{-}stgy\ cdcl_W^{**}]$ 
   $cdcl_W\text{-}merge\text{-}stgy\text{-}rtrancp\text{-}cdcl_W$  unfolding  $full\text{-}def$  by  $auto$ 
then have  $inv'$ :  $cdcl_W\text{-}all\text{-}struct\text{-}inv\ V$  using  $inv\ rtrancp\text{-}cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}inv$  by  $blast$ 
have  $cdcl_W\text{-}s'^{**} R V$ 
  using  $\langle ?fw \rangle$  by  $(simp\ add:\ full\text{-}def\ inv\ rtrancp\text{-}cdcl_W\text{-}merge\text{-}stgy\text{-}rtrancp\text{-}cdcl_W\text{-}s')$ 
moreover have  $no\text{-}step\ cdcl_W\text{-}s'\ V$ 
proof cases
  assume  $conflicting\ V = None$ 
  then show ?thesis
    by  $(metis\ inv'\ \langle full\ cdcl_W\text{-}merge\text{-}stgy\ R\ V \rangle\ full\text{-}def$ 
       $no\text{-}step\text{-}cdcl_W\text{-}merge\text{-}stgy\text{-}no\text{-}step\text{-}cdcl_W\text{-}s')$ 
  next
    assume  $confl\text{-}V$ :  $conflicting\ V \neq None$ 
    then have  $no\text{-}step\ cdcl_W\text{-}bj\ V$ 
    using  $rtrancp\text{-}cdcl_W\text{-}merge\text{-}stgy\text{-}no\text{-}step\text{-}cdcl_W\text{-}bj$  by  $(meson\ \langle full\ cdcl_W\text{-}merge\text{-}stgy\ R\ V \rangle$ 
       $assms(1)\ full\text{-}def)$ 
    then show ?thesis using  $confl\text{-}V$  by  $(fastforce\ simp:\ cdcl_W\text{-}s'.simps\ full1\text{-}def\ cdcl_W\text{-}cp.simps$ 
       $dest!\ ::\ trancpD)$ 
  qed
ultimately show ?s' unfolding  $full\text{-}def$  by  $blast$ 
qed

```

```

lemma  $full\text{-}cdcl_W\text{-}stgy\text{-}full\text{-}cdcl_W\text{-}merge$ :
assumes
   $conflicting\ R = None$  and
   $inv$ :  $cdcl_W\text{-}all\text{-}struct\text{-}inv\ R$ 
shows  $full\ cdcl_W\text{-}stgy\ R\ V \longleftrightarrow full\ cdcl_W\text{-}merge\text{-}stgy\ R\ V$ 
by  $(simp\ add:\ assms(1)\ full\text{-}cdcl_W\text{-}s'\text{-}full\text{-}cdcl_W\text{-}merge\text{-}restart\ full\text{-}cdcl_W\text{-}stgy\text{-}iff\text{-}full\text{-}cdcl_W\text{-}s'$ 
   $inv)$ 

```

```

lemma  $full\text{-}cdcl_W\text{-}merge\text{-}stgy\text{-}final\text{-}state\text{-}conclusive'$ :
fixes  $S' :: 'st$ 
assumes  $full$ :  $full\ cdcl_W\text{-}merge\text{-}stgy\ (init\text{-}state\ N)\ S'$ 
and  $no\text{-}d$ :  $distinct\text{-}mset\text{-}mset\ N$ 
shows  $(conflicting\ S' = Some\ \{\#\} \wedge unsatisfiable\ (set\text{-}mset\ N))$ 
   $\vee (conflicting\ S' = None \wedge trail\ S' \models_{asm}\ N \wedge satisfiable\ (set\text{-}mset\ N))$ 

```

```

proof –
have  $cdcl_W\text{-}all\text{-}struct\text{-}inv\ (init\text{-}state\ N)$ 
  using  $no\text{-}d$  unfolding  $cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def$  by  $auto$ 
moreover have  $conflicting\ (init\text{-}state\ N) = None$ 
  by  $auto$ 
ultimately show ?thesis
  by  $(simp\ add:\ full\ full\text{-}cdcl_W\text{-}stgy\text{-}final\text{-}state\text{-}conclusive\text{-}from\text{-}init\text{-}state$ 
     $full\text{-}cdcl_W\text{-}stgy\text{-}full\text{-}cdcl_W\text{-}merge\ no\text{-}d)$ 
qed

```

end

19.6 Adding Restarts

```

locale  $cdcl_W\text{-}restart =$ 
   $cdcl_W\ trail\ init\text{-}cls\ learned\text{-}cls\ backtrack\text{-}lvl\ conflicting\ cons\text{-}trail\ tl\text{-}trail$ 
   $add\text{-}init\text{-}cls$ 
   $add\text{-}learned\text{-}cls\ remove\text{-}cls\ update\text{-}backtrack\text{-}lvl\ update\text{-}conflicting\ init\text{-}state$ 
   $restart\text{-}state$ 

```

```

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 option 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 option  $\Rightarrow$  'st  $\Rightarrow$  'st and

  init-state :: 'v 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!: relpoup-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!: relpoup-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 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  $\text{auto}$ 
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  $\text{auto}$ 
moreover
  have  $\text{atms-of } C \subseteq \text{atms-of-msu } (\text{learned-clss } S)$ 
    using  $C$  by  $\text{auto}$ 
  then have  $\text{atms-of } C \subseteq \text{atms-of-msu } (\text{init-clss } S)$ 
    using  $\text{inv}$  unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$   $\text{no-strange-atm-def}$  by  $\text{force}$ 
moreover have  $\text{finite } (\text{atms-of-msu } (\text{init-clss } S))$ 
  using  $\text{inv}$  unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$  by  $\text{auto}$ 
ultimately show  $C \in \text{simple-clss } (\text{atms-of-msu } (\text{init-clss } S))$ 
  using  $\text{distinct-mset-not-tautology-implies-in-simple-clss}$   $\text{simple-clss-mono}$ 
  by  $\text{blast}$ 
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**

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 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** 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** ($\text{metis } \text{add.commute } f \ \text{less-or-eq-imp-le } \text{snd-g}$
 $\text{not-bounded-nat-exists-larger not-le ordered-cancel-comm-monoid-diff-class.le-iff-add}$)

obtain k **where**

$f\text{-g-}k$: $f \ (\text{snd } (g \ k)) > \text{card } (\text{simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$ **and**

$k > \text{card } (\text{simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$

using $\text{not-bounded-nat-exists-larger}[OF \ \text{unbounded-f-g}]$ **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 relpoup-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 relpoup-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 (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 (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 (simp add: (finite (atms-of-msu (init-clss (fst (g 0))))) simple-clss-finite
    card-mono leD)
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 *rtrancp-cdcl_W-merge-stgy-distinct-mset-clauses*[*of* $S\ T$] **unfolding** *full1-def*
 by (*auto dest: relpowp-imp-rtrancp*)
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:

$(cdcl_W\text{-stgy} \sim (card\ (set\text{-mset}\ (learned\text{-clss}\ T)) - card\ (set\text{-mset}\ (learned\text{-clss}\ S))))\ S\ T \implies$
 $card\ (set\text{-mset}\ (learned\text{-clss}\ T)) - card\ (set\text{-mset}\ (learned\text{-clss}\ S)) > f\ n \implies$
 $restart\ T\ U \implies$

$cdcl_W\text{-with-restart}\ (S, n)\ (U, Suc\ n) \mid$

restart-full: $full1\ cdcl_W\text{-stgy}\ S\ T \implies cdcl_W\text{-with-restart}\ (S, n)\ (T, Suc\ n)$

lemma *cdcl_W-with-restart-rtrancp-cdcl_W*:

$cdcl_W\text{-with-restart}\ S\ T \implies cdcl_W^{**}\ (fst\ S)\ (fst\ T)$

apply (*induction rule: cdcl_W-with-restart.induct*)

by (*auto dest!: relpowp-imp-rtrancp trancp-into-rtrancp fw-r-rf*

cdcl_W-rf.restart rtrancp-cdcl_W-stgy-rtrancp-cdcl_W cdcl_W-merge-restart-cdcl_W

simp: full1-def)

lemma *cdcl_W-with-restart-increasing-number*:

$cdcl_W\text{-with-restart}\ S\ T \implies snd\ T = 1 + snd\ S$

by (*induction rule: cdcl_W-with-restart.induct*) *auto*

lemma $full1\ cdcl_W\text{-stgy}\ S\ T \implies cdcl_W\text{-with-restart}\ (S, n)\ (T, Suc\ n)$

using *restart-full* **by** *blast*

lemma *cdcl_W-with-restart-init-clss*:

$cdcl_W\text{-with-restart}\ S\ T \implies cdcl_W\text{-M-level-inv}\ (fst\ S) \implies init\text{-clss}\ (fst\ S) = init\text{-clss}\ (fst\ T)$

using *cdcl_W-with-restart-rtrancp-cdcl_W rtrancp-cdcl_W-init-clss* **by** *blast*

lemma

$wf\ \{(T, S). cdcl_W\text{-all-struct-inv}\ (fst\ S) \wedge cdcl_W\text{-with-restart}\ S\ T\}$

proof (*rule ccontr*)

assume $\neg ?thesis$

then obtain g **where**

$g: \bigwedge i. cdcl_W\text{-with-restart}\ (g\ i)\ (g\ (Suc\ i))$ **and**

$inv: \bigwedge i. cdcl_W\text{-all-struct-inv}\ (fst\ (g\ i))$

unfolding *wf-iff-no-infinite-down-chain* **by** *fast*

{ fix i

have $init\text{-clss}\ (fst\ (g\ i)) = init\text{-clss}\ (fst\ (g\ 0))$

apply (*induction i*)

apply *simp*

using $g\ inv$ **unfolding** *cdcl_W-all-struct-inv-def* **by** (*metis cdcl_W-with-restart-init-clss*)

} note $init\text{-}g = this$

let $?S = g\ 0$

have $finite\ (atms\text{-of-msu}\ (init\text{-clss}\ (fst\ ?S)))$

using inv **unfolding** *cdcl_W-all-struct-inv-def* **by** *auto*

have $snd\text{-}g: \bigwedge i. snd\ (g\ i) = i + snd\ (g\ 0)$

apply (*induct-tac i*)

apply *simp*

by (*metis Suc-eq-plus1-left add-Suc cdcl_W-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*: *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: $f \ (\text{snd } (g \ k)) > \text{card } (\text{simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$ **and**
 $k > \text{card } (\text{simple-clss } (\text{atms-of-msu } (\text{init-clss } (\text{fst } ?S))))$
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 card (set-mset (learned-clss T)) - card (set-mset (learned-clss (fst (g k))))
  > card (simple-clss (atms-of-msu (init-clss (fst ?S))))
  unfolding m[symmetric] using  $m > f \ (\text{snd } (g \ k))$  f-g-k by linarith
then have card (set-mset (learned-clss T))
  > card (simple-clss (atms-of-msu (init-clss (fst ?S))))
  by linarith
moreover
  have init-clss (fst (g k)) = init-clss T
    using  $\langle \text{cdcl}_W\text{-stgy}^{**} \ (\text{fst } (g \ k)) \ T \rangle$  rtranclp-cdclW-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 (simp add:  $\langle \text{finite } (\text{atms-of-msu } (\text{init-clss } (\text{fst } (g \ 0)))) \rangle$  simple-clss-finite
    card-mono leD)
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 rtranclp-cdclW-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-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
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 $\forall n \text{ na. } \neg (1::\text{nat}) \leq n \vee 1 \leq n \wedge \text{na}$

by (*meson one-le-power*)

then have $f1: (1::\text{nat}) \leq 2^{(?k-1)}$

using *one-le-numeral* **by** *blast*

have $f2: i - 2^{(?k-1)} + 2^{(?k-1)} = i$

using $\langle 2^{(?k-1)} \leq i \wedge i < 2^{?k} - 1 \rangle$ *le-add-diff-inverse2* **by** *blast*

have $f3: 2^{?k} - 1 \neq \text{Suc } 0$

using $f1 \langle 2^{(?k-1)} \leq i \wedge i < 2^{?k} - 1 \rangle$ **by** *linarith*

have $2^{?k} - (1::\text{nat}) \neq 0$

using $\langle 2^{(?k-1)} \leq i \wedge i < 2^{?k} - 1 \rangle$ *gr-implies-not0* **by** *blast*

then have $f4: 2^{?k} \neq (1::\text{nat})$

by *linarith*

have $f5: \forall n \text{ na. if } \text{na} = 0 \text{ then } (n::\text{nat}) \wedge \text{na} = 1 \text{ else } n \wedge \text{na} = n * n \wedge (\text{na} - 1)$

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 $i = luby-sequence-core\ (i - 2 \wedge (k - 1) + 1)$
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  $\bigwedge k k'. 2 \wedge (k - \text{Suc } 0) \leq i \implies i < 2 \wedge k - \text{Suc } 0 \implies 2 \wedge (k' - \text{Suc } 0) \leq i \implies$ 
 $i < 2 \wedge k' - \text{Suc } 0 \implies k = k'$ 
  by (meson different-luby-decomposition-false linorder-neqE-nat)
then have k:  $(\text{SOME } k. 2 \wedge (k - \text{Suc } 0) \leq i \wedge i < 2 \wedge k - \text{Suc } 0) = k$ 
  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  $(2^{b+1} - 1) = 2^b$ 
    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  $2^{b+1} - 1$ ] 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:  $(0::nat) = 2^0 - 1$ 
    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 Suc n = 2 ^ k - 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: Suc n - 2 ^ (k - 1) + 1 < 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 trail init-clss learned-clss backtrack-lvl conflicting cons-trail tl-trail
  add-init-cls
  add-learned-clss remove-clss update-backtrack-lvl update-conflicting init-state
  restart-state
for
  ur :: nat and
  trail :: 'st ⇒ ('v, 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 option and
  cons-trail :: ('v, nat, 'v clause) marked-lit ⇒ 'st ⇒ 'st and
  tl-trail :: 'st ⇒ 'st and
  add-init-clss :: 'v clause ⇒ 'st ⇒ 'st and
  add-learned-clss remove-clss :: 'v clause ⇒ 'st ⇒ 'st and
  update-backtrack-lvl :: nat ⇒ 'st ⇒ 'st and
  update-conflicting :: 'v clause option ⇒ 'st ⇒ 'st and

  init-state :: 'v clauses ⇒ 'st and
  restart-state :: 'st ⇒ 'st
begin

sublocale cdclW-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*
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
 $\text{cdcl}_W: \text{cdcl}_W\text{-stgy } S \text{ } T$ **and**
 $\text{inv-s}: \text{cdcl}_W\text{-stgy-invariant } S$ **and**
 $\text{inv}: \text{cdcl}_W\text{-all-struct-inv } S$
shows
 $\text{cdcl}_W\text{-stgy-invariant } T$
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 *rtrancp-cdcl_W-stgy-cdcl_W-stgy-invariant*:

assumes
 $\text{cdcl}_W: \text{cdcl}_W\text{-stgy}^{**} S \text{ } T$ **and**
 $\text{inv-s}: \text{cdcl}_W\text{-stgy-invariant } S$ **and**
 $\text{inv}: \text{cdcl}_W\text{-all-struct-inv } S$
shows
 $\text{cdcl}_W\text{-stgy-invariant } T$
using *assms* **apply** (induction)
apply *simp*
using *cdcl_W-stgy-cdcl_W-stgy-invariant* *rtrancp-cdcl_W-all-struct-inv-inv*
rtrancp-cdcl_W-stgy-rtrancp-cdcl_W **by** *blast*

abbreviation *decr-bt-lvl* **where**

decr-bt-lvl $S \equiv \text{update-backtrack-lvl } (\text{backtrack-lvl } S - 1) \text{ } S$

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 $C \ [] \ S = S \ |$
cut-trail-wrt-clause $C \ (\text{Marked } L - \# \ M) \ S =$
 $(\text{if } -L \in \# \ C \text{ then } S$
 $\quad \text{else } \text{cut-trail-wrt-clause } C \ M \ (\text{decr-bt-lvl } (\text{tl-trail } S))) \ |$
cut-trail-wrt-clause $C \ (\text{Propagated } L - \# \ M) \ S =$
 $(\text{if } -L \in \# \ C \text{ then } S$

else cut-trail-wrt-clause C M (tl-trail S))

definition *add-new-clause-and-update* :: 'v literal multiset \Rightarrow 'st \Rightarrow 'st **where**

add-new-clause-and-update C S =

(if trail S \models_{as} CNot C

then update-conflicting (Some C) (add-init-cls C (cut-trail-wrt-clause C (trail S) S))

else add-init-cls C S)

thm *cut-trail-wrt-clause.induct*

lemma *init-clss-cut-trail-wrt-clause[simp]:*

init-clss (cut-trail-wrt-clause C M S) = init-clss S

by (*induction rule: cut-trail-wrt-clause.induct*) *auto*

lemma *learned-clss-cut-trail-wrt-clause[simp]:*

learned-clss (cut-trail-wrt-clause C M S) = learned-clss S

by (*induction rule: cut-trail-wrt-clause.induct*) *auto*

lemma *conflicting-clss-cut-trail-wrt-clause[simp]:*

conflicting (cut-trail-wrt-clause C M S) = conflicting S

by (*induction rule: cut-trail-wrt-clause.induct*) *auto*

lemma *trail-cut-trail-wrt-clause:*

$\exists M. \text{ trail } S = M @ \text{ trail } (\text{cut-trail-wrt-clause } C (\text{trail } S) S)$

proof (*induction trail S arbitrary:S 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 S)]* **and** *M = this(2)[symmetric]*

then show ?*case* **using** *Cons-eq-appendI* **by** *fastforce+*

next

case (*proped L l M*) **note** *IH = this(1)[of tl-trail S]* **and** *M = this(2)[symmetric]*

then show ?*case* **using** *Cons-eq-appendI* **by** *fastforce+*

qed

lemma *n-dup-no-dup-trail-cut-trail-wrt-clause[simp]:*

assumes *n-d: no-dup (trail T)*

shows *no-dup (trail (cut-trail-wrt-clause C (trail T) T))*

proof –

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** *auto*

show ?*thesis*

using *n-d unfolding arg-cong[OF M, of no-dup]* **by** *auto*

qed

lemma *cut-trail-wrt-clause-backtrack-lvl-length-marked:*

assumes

backtrack-lvl T = length (get-all-levels-of-marked (trail T))

shows

backtrack-lvl (cut-trail-wrt-clause C (trail T) T) =

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 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)
  show ?case
  proof (cases count C (-L) = 0)
  case False
  then show ?thesis
    using IH M bt by (auto simp: true-annots-true-cls)
  next
  case True
  obtain mma :: 'v literal multiset where
    f6: (mma  $\in$   $\{\{\#- l\# \mid l. l \in \# C\} \longrightarrow M \models_a mma\} \longrightarrow M \models_{as} \{\{\#- l\# \mid l. l \in \# C\}$ )
    using true-annots-def by maura
  have mma  $\in$   $\{\{\#- l\# \mid l. l \in \# C\} \longrightarrow \text{trail } T \models_a mma\}$ 
    using CNot-def M bt by (metis (no-types) true-annots-def)
  then have M  $\models_{as} \{\{\#- l\# \mid l. l \in \# C\}$ 
    using f6 True M bt by force
  then show ?thesis
    using IH true-annots-true-cls M by (auto simp: CNot-def)

```

```

qed
next
case (proped L l M) note IH = this(1)[of tl-trail T] and M = this(2)[symmetric] and bt = this(3)
show ?case
proof (cases count C (-L) = 0)
case False
then show ?thesis
using IH M bt by (auto simp: true-annots-true-cls)
next
case True
obtain mma :: 'v literal multiset where
f6: (mma ∈ {{#- l#} | l. l ∈# C} → M ⊨a mma) → M ⊨as {{#- l#} | l. l ∈# C}
using true-annots-def by moura
have mma ∈ {{#- l#} | l. l ∈# C} → trail T ⊨a mma
using CNot-def M bt by (metis (no-types) true-annots-def)
then have M ⊨as {{#- l#} | l. l ∈# C}
using f6 True M bt by force
then show ?thesis
using IH true-annots-true-cls M by (auto simp: CNot-def)
qed
qed

lemma cut-trail-wrt-clause-hd-trail-in-or-empty-trail:
((∀ L ∈# C. -L ∉ lits-of (trail T)) ∧ trail (cut-trail-wrt-clause C (trail T) T) = [])
∨ (-lit-of (hd (trail (cut-trail-wrt-clause C (trail T) T))) ∈# C
∧ length (trail (cut-trail-wrt-clause C (trail T) T)) ≥ 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-conflict:

$trail S \models_{asm} init-clss S \Rightarrow distinct-mset C \Rightarrow conflicting S = None \Rightarrow$
 $trail S \models_{as} CNot C \Rightarrow$
 $full\ cdcl_W\ stgy$
 $(update-conflicting (Some C) (add-init-cls C (cut-trail-wrt-clause C (trail S) S))) T \Rightarrow$
 $incremental-cdcl_W S T \mid$

add-no-conflict:

$trail S \models_{asm} init-clss S \Rightarrow distinct-mset C \Rightarrow conflicting S = None \Rightarrow$
 $\neg trail S \models_{as} CNot C \Rightarrow$
 $full\ cdcl_W\ stgy (add-init-cls C S) T \Rightarrow$
 $incremental-cdcl_W S T$

inductive $add-learned-clss :: 'st \Rightarrow 'v clauses \Rightarrow 'st \Rightarrow bool$ **for** $S :: 'st$ **where**

add-learned-clss-nil: $add-learned-clss S \{\#\} S \mid$

add-learned-clss-plus:

add-learned-clss $S A T \implies \text{add-learned-clss } S (\{ \#x\# \} + A) (\text{add-learned-clss } x T)$
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* $T = \text{trail } S$
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* $T = U + \text{learned-clss } S$
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* $T = \text{init-clss } S$
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* $T = \text{conflicting } S$
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* $T = \text{backtrack-lvl } S$
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) {#} $T \implies T = \text{init-state } N$
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 #} $T \implies T = \text{add-learned-clss } C (\text{init-state } N)$
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-conf-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* $T \models_{as} C \text{Not } C$ **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  $?T = \text{update-conflicting}$  ( $\text{Some } C$ ) ( $\text{add-init-cls } C$  ( $\text{cut-trail-wrt-clause } C$  ( $\text{trail } T$ )  $T$ ))
  obtain  $M$  where
     $M: \text{trail } T = M @ \text{trail} (\text{cut-trail-wrt-clause } C (\text{trail } T) T)$ 
    using  $\text{trail-cut-trail-wrt-clause}[of\ T\ C]$  by  $\text{blast}$ 
  have  $H[\text{dest}]: \bigwedge x. x \in \text{lits-of} (\text{trail} (\text{cut-trail-wrt-clause } C (\text{trail } T) T)) \implies$ 
     $x \in \text{lits-of} (\text{trail } T)$ 
    using  $\text{inv-}T\ \text{arg-cong}[OF\ M, \text{ of } \text{lits-of}]$  by  $\text{auto}$ 
  have  $H'[\text{dest}]: \bigwedge x. x \in \text{set} (\text{trail} (\text{cut-trail-wrt-clause } C (\text{trail } T) T)) \implies x \in \text{set} (\text{trail } T)$ 
    using  $\text{inv-}T\ \text{arg-cong}[OF\ M, \text{ of } \text{set}]$  by  $\text{auto}$ 

  have  $H\text{-proped}: \bigwedge x. x \in \text{set} (\text{get-all-mark-of-propagated} (\text{trail} (\text{cut-trail-wrt-clause } C (\text{trail } T) T))) \implies x \in \text{set} (\text{get-all-mark-of-propagated} (\text{trail } T))$ 
    using  $\text{inv-}T\ \text{arg-cong}[OF\ M, \text{ of } \text{get-all-mark-of-propagated}]$  by  $\text{auto}$ 

  have  $[simp]: \text{no-strange-atm } ?T$ 
    using  $\text{inv-}T$  unfolding  $cdcl_W$ -all-struct-inv-def no-strange-atm-def add-new-clause-and-update-def
     $cdcl_W$ -M-level-inv-def
    by ( $\text{auto dest!}: H\ H'$ )

  have  $M\text{-lev}: cdcl_W$ -M-level-inv  $T$ 
    using  $\text{inv-}T$  unfolding  $cdcl_W$ -all-struct-inv-def by  $\text{blast}$ 
  then have  $\text{no-dup} (M @ \text{trail} (\text{cut-trail-wrt-clause } C (\text{trail } T) T))$ 
    unfolding  $cdcl_W$ -M-level-inv-def unfolding  $M[\text{symmetric}]$  by  $\text{auto}$ 
  then have  $[simp]: \text{no-dup} (\text{trail} (\text{cut-trail-wrt-clause } C (\text{trail } T) T))$ 
    by  $\text{auto}$ 

  have  $\text{consistent-interp} (\text{lits-of} (M @ \text{trail} (\text{cut-trail-wrt-clause } C (\text{trail } T) T)))$ 
    using  $M\text{-lev}$  unfolding  $cdcl_W$ -M-level-inv-def unfolding  $M[\text{symmetric}]$  by  $\text{auto}$ 
  then have  $[simp]: \text{consistent-interp} (\text{lits-of} (\text{trail} (\text{cut-trail-wrt-clause } C (\text{trail } T) T)))$ 
    unfolding  $\text{consistent-interp-def}$  by  $\text{auto}$ 

  have  $[simp]: cdcl_W$ -M-level-inv  $?T$ 
    using  $M\text{-lev}$   $\text{cut-trail-wrt-clause-get-all-levels-of-marked}[of\ T\ C]$ 
    unfolding  $cdcl_W$ -M-level-inv-def by ( $\text{auto dest}: H\ H'$ )
     $\text{simp: } M\text{-lev } cdcl_W$ -M-level-inv-def  $\text{cut-trail-wrt-clause-backtrack-lvl-length-marked}$ )

  have  $[simp]: \bigwedge s. s \in \# \text{learned-clss } T \implies \neg \text{tautology } s$ 
    using  $\text{inv-}T$  unfolding  $cdcl_W$ -all-struct-inv-def by  $\text{auto}$ 

  have  $\text{distinct-}cdcl_W$ -state  $T$ 
    using  $\text{inv-}T$  unfolding  $cdcl_W$ -all-struct-inv-def by  $\text{auto}$ 
  then have  $[simp]: \text{distinct-}cdcl_W$ -state  $?T$ 
    unfolding  $\text{distinct-}cdcl_W$ -state-def by  $\text{auto}$ 

  have  $cdcl_W$ -conflicting  $T$ 
    using  $\text{inv-}T$  unfolding  $cdcl_W$ -all-struct-inv-def by  $\text{auto}$ 
  have  $\text{trail } ?T \models_{as} C \text{Not } C$ 
    by ( $\text{simp add: cut-trail-wrt-clause-CNot-trail}$ )
  then have  $[simp]: cdcl_W$ -conflicting  $?T$ 
    unfolding  $cdcl_W$ -conflicting-def apply  $\text{simp}$ 
    by ( $\text{metis } M \langle cdcl_W$ -conflicting  $T \rangle \text{append-assoc } cdcl_W$ -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) ∈ set (get-all-marked-decomposition (trail ?T))
  from in-get-all-marked-decomposition-in-get-all-marked-decomposition-prepend[OF this, of M]
  obtain b' where
    (a, b' @ b) ∈ set (get-all-marked-decomposition (trail T))
    using M by auto
  then have unmark a ∪ set-mset (init-clss T) ⊨ps unmark (b' @ b)
    using decomp-T unfolding all-decomposition-implies-def by fastforce
  then have unmark a ∪ set-mset (init-clss ?T)
    ⊨ps unmark (b @ b')
    by (simp add: Un-commute)
  then show unmark a ∪ set-mset (init-clss ?T)
    ⊨ps unmark 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 *cdcl_W-all-struct-inv-add-new-clause-and-update-cdcl_W-stgy-inv:*

assumes

- inv-s*: *cdcl_W-stgy-invariant T* **and**
- inv*: *cdcl_W-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 *cdcl_W-stgy-invariant (add-new-clause-and-update C T)* (**is** *cdcl_W-stgy-invariant ?T'*)

proof –

have *cdcl_W-all-struct-inv ?T'*

using *cdcl_W-all-struct-inv-add-new-clause-and-update-cdcl_W-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 *cdcl_W-M-level-inv-decomp(2) cdcl_W-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*
cdcl_W-M-level-inv-def cdcl_W-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)  $\forall L \in \#C. - L \notin \text{lits-of } (\text{trail } T) \text{ and } \text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T) = []$ 
| (not-false)  $- \text{lit-of } (\text{hd } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T))) \in \# C \text{ and }$ 
   $1 \leq \text{length } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T))$ 
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 cdclW-all-struct-inv ?T' unfolding cdclW-all-struct-inv-def cdclW-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 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)
  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)
    then have atm-of ?L  $\notin$  atm-of ' lits-of (tl (trail (cut-trail-wrt-clause C (trail T) T)))
      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 (trail (cut-trail-wrt-clause C (trail T) T)) (-?L)
     $= \text{length } (\text{get-all-levels-of-marked } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T)))$ 
    using get-level-get-rev-level-get-all-levels-of-marked[OF
      atm-of ?L  $\notin$  atm-of ' lits-of (tl (trail (cut-trail-wrt-clause C (trail T) T))),
      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)

  have L': length (get-all-levels-of-marked (trail (cut-trail-wrt-clause C (trail T) T)))
     $= \text{backtrack-lvl } (\text{cut-trail-wrt-clause } C (\text{trail } T) T)$ 
    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)

  have [simp]: no-smaller-confl (update-conflicting (Some 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 cdclW-stgy-invariant-def by auto
have (MT @ M') @ Marked K i # M = trail T
  using MT 1(1) by auto
thus False using D-T ⟨no-smaller-confl T⟩ 1(3) unfolding no-smaller-confl-def by blast
next
case DC note -[simp] = this
then have atm-of (−?L) ∈ atm-of ‘ (lits-of M)
  using 1(3) C in-CNot-implies-uminus(2) by blast
moreover
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-cdcl_W-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 = Some {#} ∧ unsatisfiable (set-mset (init-clss S))
  ∨ conflicting T = None ∧ 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.rtranclp-cdclW-stgy-rtranclp-cdclW cdclW-axioms full full-def inv
    rtranclp-cdclW-all-struct-inv-inv)
  by (metis full full-def inv inv-s rtranclp-cdclW-stgy-cdclW-stgy-invariant)
ultimately have conflicting T = Some {#} ∧ unsatisfiable (set-mset (init-clss T))

```

\vee conflicting $T = \text{None} \wedge \text{trail } T \models_{\text{asm}} \text{init-clss } T$
using $\text{cdcl}_W\text{-stgy-final-state-conclusive[of } T] \text{ full}$
unfolding $\text{cdcl}_W\text{-all-struct-inv-def cdcl}_W\text{-stgy-invariant-def full-def}$ **by** *fast*
moreover have $\text{consistent-interp (lits-of (trail } T))$
using $\langle \text{cdcl}_W\text{-all-struct-inv } T \rangle$ **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def cdcl}_W\text{-M-level-inv-def}$
by *auto*
moreover have $\text{init-clss } S = \text{init-clss } T$
using *inv* **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$
by $(\text{metis rtranclp-cdcl}_W\text{-stgy-no-more-init-clss full full-def})$
ultimately show $?thesis$
by $(\text{metis satisfiable-carac' true-annot-def true-annots-def true-clss-def})$
qed

lemma *incremental-cdcl_W-inv*:

assumes

inc: $\text{incremental-cdcl}_W \ S \ T$ **and**

inv: $\text{cdcl}_W\text{-all-struct-inv } S$ **and**

s-inv: $\text{cdcl}_W\text{-stgy-invariant } S$

shows

$\text{cdcl}_W\text{-all-struct-inv } T$ **and**

$\text{cdcl}_W\text{-stgy-invariant } T$

using *inc*

proof (*induction*)

case $(\text{add-confl } C \ T)$

let $?T = (\text{update-conflicting } (\text{Some } C) (\text{add-init-cls } C (\text{cut-trail-wrt-clause } C (\text{trail } S) \ S)))$

have $\text{cdcl}_W\text{-all-struct-inv } ?T$ **and** $\text{inv-s-}T$: $\text{cdcl}_W\text{-stgy-invariant } ?T$

using $\text{add-confl.hyps}(1,2,4) \text{ add-new-clause-and-update-def}$

$\text{cdcl}_W\text{-all-struct-inv-add-new-clause-and-update-cdcl}_W\text{-all-struct-inv inv}$ **apply** *auto*[1]

using $\text{add-confl.hyps}(1,2,4) \text{ add-new-clause-and-update-def}$

$\text{cdcl}_W\text{-all-struct-inv-add-new-clause-and-update-cdcl}_W\text{-stgy-inv inv s-inv}$ **by** *auto*

case 1 show $?case$

by $(\text{metis add-confl.hyps}(1,2,4,5) \text{ add-new-clause-and-update-def}$

$\text{cdcl}_W\text{-all-struct-inv-add-new-clause-and-update-cdcl}_W\text{-all-struct-inv}$

$\text{rtranclp-cdcl}_W\text{-all-struct-inv-inv rtranclp-cdcl}_W\text{-stgy-rtranclp-cdcl}_W \text{ full-def inv})$

case 2 show $?case$

by $(\text{metis inv-s-}T \text{ add-confl.hyps}(1,2,4,5) \text{ add-new-clause-and-update-def}$

$\text{cdcl}_W\text{-all-struct-inv-add-new-clause-and-update-cdcl}_W\text{-all-struct-inv full-def inv}$

$\text{rtranclp-cdcl}_W\text{-stgy-cdcl}_W\text{-stgy-invariant})$

next

case $(\text{add-no-confl } C \ T)$

case 1

have $\text{cdcl}_W\text{-all-struct-inv } (\text{add-init-cls } C \ S)$

using *inv* $\langle \text{distinct-mset } C \rangle$ **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def no-strange-atm-def}$

$\text{cdcl}_W\text{-M-level-inv-def distinct-cdcl}_W\text{-state-def cdcl}_W\text{-conflicting-def cdcl}_W\text{-learned-clause-def}$

by $(\text{auto simp: all-decomposition-implies-insert-single clauses-def})$

then show $?case$

using $\text{add-no-confl}(5)$ **unfolding** *full-def* **by** $(\text{auto intro: rtranclp-cdcl}_W\text{-stgy-cdcl}_W\text{-all-struct-inv})$

case 2 have $\text{cdcl}_W\text{-stgy-invariant } (\text{add-init-cls } C \ S)$

using *s-inv* $(\neg \text{trail } S \models_{\text{as}} C \text{Not } C)$ *inv* **unfolding** $\text{cdcl}_W\text{-stgy-invariant-def no-smaller-confl-def}$

$\text{eq-commute[of - trail -]} \text{ cdcl}_W\text{-M-level-inv-def cdcl}_W\text{-all-struct-inv-def}$

by $(\text{auto simp: true-annots-true-cls-def-iff-negation-in-model clauses-def split: split-if-asm})$

then show $?case$

by $(\text{metis } \langle \text{cdcl}_W\text{-all-struct-inv } (\text{add-init-cls } C \ S) \rangle \text{ add-no-confl.hyps}(5) \text{ full-def}$

$\text{rtranclp-cdcl}_W\text{-stgy-cdcl}_W\text{-stgy-invariant})$

qed

lemma *rtranclp-incremental-cdcl_W-inv*:

assumes

inc: *incremental-cdcl_W** S T* **and**

inv: *cdcl_W-all-struct-inv S* **and**

s-inv: *cdcl_W-stgy-invariant S*

shows

cdcl_W-all-struct-inv T **and**

cdcl_W-stgy-invariant T

using *inc* **apply** *induction*

using *inv* **apply** *simp*

using *s-inv* **apply** *simp*

using *incremental-cdcl_W-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 = Some {#} \wedge unsatisfiable (set-mset (init-cls T))*

\vee *conflicting T = None \wedge trail T \models_{asm} init-cls T \wedge satisfiable (set-mset (init-cls 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 = Some {#} \wedge unsatisfiable (set-mset (init-cls T))*

\vee *conflicting T = None \wedge trail T \models_{asm} init-cls T \wedge satisfiable (set-mset (init-cls 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  $\exists L' \in \text{set } M. \text{is-marked } L'$ 
proof (rule ccontr)
  assume  $\neg ?thesis$ 
  then have  $H: \{L' \in \text{set } M. \text{is-marked } L'\} = \{\}$ 
  by auto
  show False using n unfolding H by auto
qed
then obtain  $L' M' M''$  where
   $M: M = M' @ L' \# M''$  and
   $L': \text{is-marked } L'$  and
   $nm: \forall m \in \text{set } M'. \neg \text{is-marked } m$ 
  by (auto elim!: split-list-first-propE)
have  $\text{Suc } n = \text{card } \{L' \in \text{set } M. \text{is-marked } L'\}$ 
  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  $L' n\text{-d}$  unfolding M by auto
moreover have  $L' \notin \{L' \in \text{set } M''. \text{is-marked } L'\}$ 
  using  $n\text{-d}$  unfolding M by auto
ultimately have  $n = \text{card } \{L'' \in \text{set } M''. \text{is-marked } L''\}$ 
  using n  $L'$  by auto
then have  $P (L' \# M'')$  using IH  $L' n\text{-d}$  M by auto
then show ?case using append[of  $L' \# M'' L M$ ] nm L  $n\text{-d}$  unfolding M by blast
qed

```

lemma trail-bloc-induction:

```

assumes
  n-d: 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 append-nm[of [] M] nil 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  $n\text{-d}$  unfolding M apply simp
  using nil apply simp
  using append apply simp
  using  $L'$  by auto

```


then show *?thesis*
using *append-nm[of - M] nm unfolding M by simp*
qed

inductive *Tcons* :: ('v, nat, 'v clause) marked-lits \Rightarrow ('v, nat, 'v clause) marked-lits \Rightarrow bool
for *M* :: ('v, nat, 'v clause) marked-lits **where**
Tcons M [] |
Tcons M M' \Rightarrow M = M'' @ M' \Rightarrow ($\forall m \in \text{set } M''. \neg \text{is-marked } m$) \Rightarrow Tcons M (M'' @ M') |
Tcons M M' \Rightarrow is-marked L \Rightarrow M = M''' @ L # M'' @ M' \Rightarrow ($\forall m \in \text{set } M''. \neg \text{is-marked } m$) \Rightarrow
Tcons M (L # M'' @ M')

lemma *Tcons-same-end*: *Tcons M M' \Rightarrow $\exists M''. M = M'' @ M'$*
by (*induction rule: Tcons.induct*) *auto*

end

end

21 2-Watched-Literal

theory *CDCL-Two-Watched-Literals*
imports *CDCL-WNOT*
begin

21.1 Datastructure and Access Functions

Only the 2-watched literals have to be verified here: the backtrack level and the trail that appear in the state are not related to the 2-watched algorithm.

datatype 'v *twl-clause* =
TWL-Clause (watched: 'v) (unwatched: 'v)

abbreviation *raw-clause* :: 'v clause *twl-clause* \Rightarrow 'v clause **where**
raw-clause C \equiv watched C + unwatched C

datatype ('a, 'b, 'c, 'd) *twl-state* =
TWL-State (trail: 'a list) (init-clss: 'b)
(learned-clss: 'b) (backtrack-lvl: 'c)
(conflicting: 'd option)

type-synonym ('v, 'lvl, 'mark) *twl-state-abs* =
 (('v, 'lvl, 'mark) marked-lit, 'v clause *twl-clause* multiset, 'lvl, 'v clause) *twl-state*

abbreviation *raw-init-clss* **where**
raw-init-clss S \equiv image-mset raw-clause (init-clss S)

abbreviation *raw-learned-clss* **where**
raw-learned-clss S \equiv image-mset raw-clause (learned-clss S)

abbreviation *clauses* **where**
clauses S \equiv init-clss S + learned-clss S

abbreviation *raw-clauses* **where**
raw-clauses S \equiv image-mset raw-clause (clauses S)

definition

candidates-propagate :: ('v, 'lvl, 'mark) twl-state-abs \Rightarrow ('v literal \times 'v clause) set

where

candidates-propagate $S =$

$\{(L, \text{raw-clause } C) \mid L \vdash C.$

$C \in \# \text{ clauses } S \wedge \text{watched } C - \text{mset-set } (\text{uminus ' lits-of } (\text{trail } S)) = \{\#L\# \} \wedge$

$\text{undefined-lit } (\text{trail } S) \ L\}$

definition *candidates-conflict* :: ('v, 'lvl, 'mark) twl-state-abs \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 ($a \# l$) $c = (\text{if } a = c \text{ then } 0 \text{ else } 1 + \text{index } l \ c)$

lemma *index-nth*:

$a \in \text{set } l \implies l ! (\text{index } l \ a) = a$

by (*induction* l) *auto*

21.2 Invariants

We need the following property about updates: 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 clause twl-clause

\Rightarrow bool

where

watched-decided-most-recently $M \ (TWL\text{-Clause } W \ UW) \longleftrightarrow$

$(\forall L' \in \# W. \forall L \in \# UW.$

$-L' \in \text{lits-of } M \longrightarrow -L \in \text{lits-of } M \longrightarrow L \notin \# W \longrightarrow$

$\text{index } (\text{map lit-of } M) \ (-L') \leq \text{index } (\text{map lit-of } M) \ (-L))$

Here are the invariant strictly related to the 2-WL data structure.

primrec *wf-tw-cl* :: ('v, 'lvl, 'mark) marked-lit list \Rightarrow 'v clause twl-clause \Rightarrow bool **where**

wf-tw-cl $M \ (TWL\text{-Clause } W \ UW) \longleftrightarrow$

$\text{distinct-mset } W \wedge \text{size } W \leq 2 \wedge (\text{size } W < 2 \longrightarrow \text{set-mset } UW \subseteq \text{set-mset } W) \wedge$

$(\forall L \in \# W. -L \in \text{lits-of } M \longrightarrow (\forall L' \in \# UW. L' \notin \# W \longrightarrow -L' \in \text{lits-of } M)) \wedge$

watched-decided-most-recently $M \ (TWL\text{-Clause } W \ UW)$

lemma $-L \in \text{lits-of } M \implies \{i. \text{map lit-of } M ! i = -L\} \neq \{\}$

unfolding *set-map-lit-of-lits-of* [*symmetric*] *set-conv-nth*

by (*smt Collect-empty-eq mem-Collect-eq*)

lemma *size-mset-2*: $\text{size } x1 = 2 \longleftrightarrow (\exists a \ b. x1 = \{\#a, \#b\})$

by (*metis* (*no-types*, *hide-lams*) *Suc-eq-plus1 one-add-one size-1-singleton-mset*

size-Diff-singleton size-Suc-Diff1 size-eq-Suc-imp-eq-union size-single union-single-eq-diff

union-single-eq-member)

lemma *distinct-mset-size-2*: $\text{distinct-mset } \{\#a, \#b\} \longleftrightarrow a \neq b$

unfolding *distinct-mset-def* **by** *auto*

lemma *wf-tw-cl-annotation-indepndant*:

assumes $M: \text{map lit-of } M = \text{map lit-of } M'$

shows *wf-tw-cl* $M \ (TWL\text{-Clause } W \ UW) \longleftrightarrow \text{wf-tw-cl } M' \ (TWL\text{-Clause } W \ UW)$

proof —

```

have lits-of M = lits-of M'
  using arg-cong[OF M, of set] by (simp add: lits-of-def)
then show ?thesis
  by (simp add: lits-of-def M)
qed

lemma wf-twl-cls-wf-twl-cls-tl:
  assumes wf: wf-twl-cls M C and n-d: no-dup M
  shows wf-twl-cls (tl M) C
proof (cases M)
case Nil
  then show ?thesis using wf
    by (cases C) (simp add: wf-twl-cls.simps[of tl -])
next
case (Cons l M') note M = this(1)
obtain W UW where C: C = TWL-Clause W UW
  by (cases C)
{ fix L L'
  assume
    LW: L ∈# W and
    LM: - L ∈ lits-of M' and
    L'UW: L' ∈# UW and
    count W L' = 0
  then have
    L'M: - L' ∈ lits-of M
    using wf by (auto simp: C M)
  have watched-decided-most-recently M C
    using wf by (auto simp: C)
  then have
    index (map lit-of M) (-L) ≤ index (map lit-of M) (-L')
    using LM L'M L'UW LW ⟨count W L' = 0⟩
    by (metis (no-types, lifting) C M bspec-mset insert-iff less-not-refl2 lits-of-cons
      watched-decided-most-recently.simps)
  then have - L' ∈ lits-of M'
    using ⟨count W L' = 0⟩ LW L'M by (auto simp: C M split: split-if-asm)
}
moreover
{
  fix L' L
  assume
    L' ∈# W and
    L ∈# UW and
    L'M: - L' ∈ lits-of M' and
    - L ∈ lits-of M' and
    L ∉# W
  moreover
    have lit-of l ≠ - L'
    using n-d unfolding M
    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 index (map lit-of M') (- L') ≤ index (map lit-of M') (- L)
    by (fastforce simp: M C split: split-if-asm)
}
}

```

moreover have *distinct-mset* W **and** *size* $W \leq 2$ **and** (*size* $W < 2 \longrightarrow \text{set-mset } UW \subseteq \text{set-mset } W$)
using *wf* **by** (*auto simp*: $C\ M$)
ultimately show *?thesis* **by** (*auto simp add*: $M\ C$)
qed

definition *wf-twl-state* :: (*'v*, *'wl*, *'mark*) *twl-state-abs* \Rightarrow *bool* **where**
wf-twl-state $S \longleftrightarrow (\forall C \in \# \text{ clauses } S. \text{wf-twl-cls } (\text{trail } S)\ C) \wedge \text{no-dup } (\text{trail } S)$

lemma *wf-candidates-propagate-sound*:

assumes *wf*: *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** *candidates-propagate-def* $MNU\text{-defs}$ **by** *blast*

obtain $W\ UW$ **where** *cw-eq*: $Cw = \text{TWL-Clause } W\ UW$

by (*cases* Cw , *blast*)

have *l-w*: $L \in \# W$

by (*metis* *Multiset.diff-le-self* $\text{cw}(3)$ *cw-eq* *mset-leD* *multi-member-last* *twl-clause.sel(1)*)

have *wf-c*: *wf-twl-cl*s $M\ Cw$

using *wf* ($Cw \in \# N + U$) **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 $\forall L' \in \text{set-mset } C - \{L\}. -L' \in \text{lits-of } M$

proof (*cases* *size* $W < 2$)

case *True*

moreover have *size* $W \neq 0$

using $\text{cw}(3)$ *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* $\text{cw}(3)$ *cw-eq* *single-not-empty*

size-1-singleton-mset *subset-mset.add-diff-inverse* *union-is-single* *twl-clause.sel(1)*)

from *True* **have** $\text{set-mset } UW \subseteq \text{set-mset } W$

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 ' lits-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 ∈ lits-of M
  by auto
  then show -L' ∈ lits-of M

proof -
  have f1: L' ∈ set-mset C
  using l' by blast
  have f2: L' ∉ {L}
  using l' by fastforce
  have ∧l L. - (l::'a literal) ∈ L ∨ l ∉ uminus ' L
  by force
  then have ∧l. - l ∈ lits-of M ∨ count {#L#} l = 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 trail S ⊨as CNot (mset-set (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: $C \in \#$ *raw-clauses S* **and**
l-mem: $L \in \#$ *C* **and**
unsat: $\text{trail } S \models_{as} CNot (\text{mset-set } (\text{set-mset } C - \{L\}))$ **and**
undef: *undefined-lit* (*trail S*) *L*
shows $(L, C) \in \text{candidates-propagate } S$

proof –

def *M* \equiv *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*: $C = \text{raw-clause } Cw$ $Cw \in \#$ $N + U$
using *c-mem* **by** *force*

obtain *W UW* **where** *cw-eq*: $Cw = \text{TWL-Clause } W \ UW$
by (*cases 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 $\implies \text{set-mset } UW \subseteq \text{set-mset } W$
 $\bigwedge L \ L'. L \in \# W \implies -L \in \text{lits-of } M \implies L' \in \# UW \implies L' \notin \# W \implies -L' \in \text{lits-of } M$
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 $L' \notin \text{uminus } ' \text{lits-of } M$

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 $\{L\} \subseteq \text{set-mset } (W - \text{mset-set } (\text{uminus } ' \text{lits-of } M))$

proof *clarify*

```

have L ∈# 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 ∈ 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 ∉# mset-set (uminus ' lits-of M)
  using Marked-Propagated-in-iff-in-lits-of undef by auto
ultimately show L ∈ set-mset (W - mset-set (uminus ' lits-of M))
  by auto
qed
qed
have unit: W - mset-set (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 ∈ candidates-conflict S
  shows trail S ⊨as CNot C ∧ C ∈# image-mset raw-clause (clauses S)
proof
  def M ≡ trail S
  def N ≡ init-clss S
  def U ≡ learned-clss S

  note MNU-defs [simp] = M-def N-def U-def

  obtain Cw where cw:
    C = raw-clause Cw
    Cw ∈# N + U
    watched Cw ⊆# mset-set (uminus ' lits-of (trail S))
  using cand[unfolded candidates-conflict-def, simplified] by auto

  obtain W UW where cw-eq: Cw = TWL-Clause W UW

```

```

by (cases 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  $\implies$  set-mset UW  $\subseteq$  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  $\forall L \in \# C. -L \in \text{ lits-of } M$ 
proof (cases W = {#})
  case True
  then have C = {#}
    using cw(1) cw-eq w-nw(2) by auto
  then show ?thesis
    by simp
next
  case False
  then obtain La where la: La  $\in \# W$ 
    using multiset-eq-iff by force
  show ?thesis
  proof
    fix L
    assume l: L  $\in \# C$ 
    show  $-L \in \text{ lits-of } M$ 
    proof (cases L  $\in \# W$ )
      case True
      thus ?thesis
        using cw(3) cw-eq by fastforce
    next
      case False
      thus ?thesis
        by (smt M-def l add-diff-cancel-left' count-diff cw(1) cw(3) la cw-eq
            diff-zero elem-mset-set finite-imageI finite-lits-of-def gr0I imageE mset-leD
            uminus-of-uminus-id twl-clause.sel(1) twl-clause.sel(2) w-nw(3))
    qed
  qed
  qed
then show trail S  $\models_{as}$  CNot C
  unfolding CNot-def true-annots-def by auto

show C  $\in \# \text{ image-mset raw-clause (clauses S) }$ 
  using cw by auto
qed

lemma wf-candidates-conflict-complete:
  assumes wf: wf-twl-state S and
    c-mem: C  $\in \# \text{ raw-clauses S }$  and
    unsat: trail S  $\models_{as}$  CNot C
  shows C  $\in \text{ candidates-conflict S }$ 
proof -
  def M  $\equiv$  trail S
  def N  $\equiv$  init-clss S

```



```

def  $U \equiv \text{learned-clss } S$ 

note  $MNU\text{-defs } [simp] = M\text{-def } N\text{-def } U\text{-def}$ 

obtain  $Cw$  where  $cw: C = \text{raw-clause } Cw \ Cw \in\# \ N + U$ 
using  $c\text{-mem}$  by  $\text{force}$ 

obtain  $W \ UW$  where  $cw\text{-eq}: Cw = \text{TWL-Clause } W \ UW$ 
by ( $\text{cases } Cw, \text{blast}$ )

have  $wf\text{-c}: wf\text{-twl-clss } M \ Cw$ 
using  $wf \ cw(2)$  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  $\bigwedge L. \ L \in\# \ C \implies -L \in \text{lits-of } M$ 
unfolding  $M\text{-def}$  using  $\text{unsat}[\text{unfolded } C\text{Not-def } \text{true-annots-def}, \text{simplified}]$  by  $\text{blast}$ 
then have  $\text{set-mset } C \subseteq \text{uminus ' lits-of } M$ 
by ( $\text{metis imageI mem-set-mset-iff subsetI uminus-of-uminus-id}$ )
then have  $\text{set-mset } W \subseteq \text{uminus ' lits-of } M$ 
using  $cw(1) \ cw\text{-eq}$  by  $\text{auto}$ 
then have  $\text{subset}: W \subseteq\# \ \text{mset-set } (\text{uminus ' lits-of } M)$ 
by ( $\text{simp add: } w\text{-nw}(1)$ )

have  $W = \text{watched } Cw$ 
using  $cw\text{-eq } \text{twl-clause.sel}(1)$  by  $\text{simp}$ 
then show  $?thesis$ 
using  $MNU\text{-defs } cw(1) \ cw(2) \ \text{subset candidates-conflict-def}$  by  $\text{blast}$ 
qed

typedef  $'v \ wf\text{-twl} = \{S::('v, \text{nat}, 'v \ \text{clause}) \ \text{twl-state-abs. } wf\text{-twl-state } S\}$ 
morphisms  $\text{rough-state-of-twl } \text{twl-of-rough-state}$ 
proof –
  have  $\text{TWL-State } ([::('v, \text{nat}, 'v \ \text{clause}) \ \text{marked-lits})$ 
     $\{\#\} \ \{\#\} \ 0 \ \text{None} \in \{S::('v, \text{nat}, 'v \ \text{clause}) \ \text{twl-state-abs. } wf\text{-twl-state } S\}$ 
    by ( $\text{auto simp: } wf\text{-twl-state-def}$ )
  then show  $?thesis$  by  $\text{auto}$ 
qed

lemma [ $\text{code abstype}$ ]:
   $\text{twl-of-rough-state } (\text{rough-state-of-twl } S) = S$ 
by ( $\text{fact } CDCL\text{-Two-Watched-Literals.wf-twl.rough-state-of-twl-inverse}$ )

lemma  $wf\text{-twl-state-rough-state-of-twl}[simp]: wf\text{-twl-state } (\text{rough-state-of-twl } S)$ 
using  $\text{rough-state-of-twl}$  by  $\text{auto}$ 

abbreviation  $\text{candidates-conflict-twl} :: 'v \ wf\text{-twl} \Rightarrow 'v \ \text{literal multiset set}$  where
 $\text{candidates-conflict-twl } S \equiv \text{candidates-conflict } (\text{rough-state-of-twl } S)$ 

abbreviation  $\text{candidates-propagate-twl} :: 'v \ wf\text{-twl} \Rightarrow ('v \ \text{literal} \times 'v \ \text{clause}) \ \text{set}$  where
 $\text{candidates-propagate-twl } S \equiv \text{candidates-propagate } (\text{rough-state-of-twl } S)$ 

```

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 literal multiset multiset **where**
clauses-twl *S* \equiv *raw-clauses* (*rough-state-of-twl* *S*)

abbreviation *init-clss-twl* :: 'a wf-twl \Rightarrow 'a literal multiset multiset **where**
init-clss-twl *S* \equiv *raw-init-clss* (*rough-state-of-twl* *S*)

abbreviation *learned-clss-twl* :: 'a wf-twl \Rightarrow 'a literal multiset multiset **where**
learned-clss-twl *S* \equiv *raw-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*)

lemma *wf-candidates-twl-conflict-complete*:

assumes

c-mem: $C \in \#$ *clauses-twl* *S* **and**

unsat: *trail-twl* *S* \models_{as} *CNot* *C*

shows $C \in$ *candidates-conflict-twl* *S*

using *c-mem* *unsat* *wf-candidates-conflict-complete* *wf-twl-state-rough-state-of-twl* **by** *blast*

abbreviation *update-backtrack-lvl* **where**

update-backtrack-lvl *k* *S* \equiv

TWL-State (*trail* *S*) (*init-clss* *S*) (*learned-clss* *S*) *k* (*conflicting* *S*)

abbreviation *update-conflicting* **where**

update-conflicting *C* *S* \equiv *TWL-State* (*trail* *S*) (*init-clss* *S*) (*learned-clss* *S*) (*backtrack-lvl* *S*) *C*

21.3 Abstract 2-WL

definition *tl-trail* **where**

tl-trail *S* =

TWL-State (*tl* (*trail* *S*)) (*init-clss* *S*) (*learned-clss* *S*) (*backtrack-lvl* *S*) (*conflicting* *S*)

locale *abstract-twl* =

fixes

watch :: ('v, nat, 'v clause) *twl-state-abs* \Rightarrow 'v clause \Rightarrow 'v clause *twl-clause* **and**

rewatch :: ('v, nat, 'v literal multiset) marked-lit \Rightarrow ('v, nat, 'v clause) *twl-state-abs* \Rightarrow

'v clause *twl-clause* \Rightarrow 'v clause *twl-clause* **and**

linearize :: 'v clauses \Rightarrow 'v clause list **and**

restart-learned :: ('v, nat, 'v clause) *twl-state-abs* \Rightarrow 'v clause *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:

no-dup (*trail* *S*) \implies *undefined-lit* (*trail* *S*) (*lit-of* *L*) \implies *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]*: $\text{linearize } \{\#\} = []$
using *linearize mset-zero-iff* **by** *blast*

definition

$\text{cons-trail} :: ('v, \text{nat}, 'v \text{ clause}) \text{ marked-lit} \Rightarrow ('v, \text{nat}, 'v \text{ clause}) \text{ twl-state-abs} \Rightarrow$
 $('v, \text{nat}, 'v \text{ clause}) \text{ twl-state-abs}$

where

$\text{cons-trail } L \ S =$
 $\text{TWL-State } (L \ \# \ \text{trail } S) \ (\text{image-mset } (\text{rewatch } L \ S) \ (\text{init-clss } S))$
 $(\text{image-mset } (\text{rewatch } L \ S) \ (\text{learned-clss } S)) \ (\text{backtrack-lvl } S) \ (\text{conflicting } S)$

definition

$\text{add-init-cls} :: 'v \text{ clause} \Rightarrow ('v, \text{nat}, 'v \text{ clause}) \text{ twl-state-abs} \Rightarrow$
 $('v, \text{nat}, 'v \text{ clause}) \text{ twl-state-abs}$

where

$\text{add-init-cls } C \ S =$
 $\text{TWL-State } (\text{trail } S) \ (\{\# \text{watch } S \ C \# \} + \text{init-clss } S) \ (\text{learned-clss } S) \ (\text{backtrack-lvl } S)$
 $(\text{conflicting } S)$

definition

$\text{add-learned-cls} :: 'v \text{ clause} \Rightarrow ('v, \text{nat}, 'v \text{ clause}) \text{ twl-state-abs} \Rightarrow$
 $('v, \text{nat}, 'v \text{ clause}) \text{ twl-state-abs}$

where

$\text{add-learned-cls } C \ S =$
 $\text{TWL-State } (\text{trail } S) \ (\text{init-clss } S) \ (\{\# \text{watch } S \ C \# \} + \text{learned-clss } S) \ (\text{backtrack-lvl } S)$
 $(\text{conflicting } S)$

definition

$\text{remove-cls} :: 'v \text{ clause} \Rightarrow ('v, \text{nat}, 'v \text{ clause}) \text{ twl-state-abs} \Rightarrow$
 $('v, \text{nat}, 'v \text{ clause}) \text{ twl-state-abs}$

where

$\text{remove-cls } C \ S =$
 $\text{TWL-State } (\text{trail } S) \ (\text{filter-mset } (\lambda D. \text{raw-clause } D \neq C) \ (\text{init-clss } S))$
 $(\text{filter-mset } (\lambda D. \text{raw-clause } D \neq C) \ (\text{learned-clss } S)) \ (\text{backtrack-lvl } S)$
 $(\text{conflicting } S)$

definition $\text{init-state} :: 'v \text{ clauses} \Rightarrow ('v, \text{nat}, 'v \text{ clause}) \text{ twl-state-abs}$ **where**

$\text{init-state } N = \text{fold add-init-cls } (\text{linearize } N) \ (\text{TWL-State } [] \ \{\#\} \ \{\#\} \ 0 \ \text{None})$

lemma *unchanged-fold-add-init-cls*:

$\text{trail } (\text{fold add-init-cls } Cs \ (\text{TWL-State } M \ N \ U \ k \ C)) = M$
 $\text{learned-clss } (\text{fold add-init-cls } Cs \ (\text{TWL-State } M \ N \ U \ k \ C)) = U$
 $\text{backtrack-lvl } (\text{fold add-init-cls } Cs \ (\text{TWL-State } M \ N \ U \ k \ C)) = k$
 $\text{conflicting } (\text{fold add-init-cls } Cs \ (\text{TWL-State } M \ N \ U \ k \ C)) = C$
by $(\text{induct } Cs \ \text{arbitrary: } N) \ (\text{auto simp: add-init-cls-def})$

lemma *unchanged-init-state[simp]*:

$\text{trail } (\text{init-state } N) = []$
 $\text{learned-clss } (\text{init-state } N) = \{\#\}$
 $\text{backtrack-lvl } (\text{init-state } N) = 0$
 $\text{conflicting } (\text{init-state } N) = \text{None}$

unfolding *init-state-def* **by** $(\text{rule unchanged-fold-add-init-cls}) +$

lemma *clauses-init-fold-add-init*:
no-dup $M \implies$
image-mset *raw-clause* (*init-clss* (*fold add-init-cls* Cs (*TWL-State* $M N U k C$))) =
mset Cs + *image-mset* *raw-clause* N
by (*induct* Cs *arbitrary*: N) (*auto simp*: *add.assoc add-init-cls-def clause-watch*)

lemma *init-clss-init-state*[*simp*]: *image-mset* *raw-clause* (*init-clss* (*init-state* N)) = N
unfolding *init-state-def* **by** (*simp add*: *clauses-init-fold-add-init linearize*)

definition *restart'* **where**
restart' $S = \text{TWL-State } [] \text{ (init-clss } S \text{) (restart-learned } S \text{) } 0 \text{ None}$
end

21.4 Instanciation of the previous locale

definition *watch-nat* :: (*nat*, *nat*, *nat clause*) *twl-state-abs* \Rightarrow *nat clause* \Rightarrow
nat clause twl-clause **where**
watch-nat $S C =$
(*let*
 $C' = \text{remdups (sorted-list-of-set (set-mset } C \text{))};$
 $\text{negation-not-assigned} = \text{filter } (\lambda L. -L \notin \text{lits-of (trail } S \text{)}) C';$
 $\text{negation-assigned-sorted-by-trail} = \text{filter } (\lambda L. L \in \# C') (\text{map } (\lambda L. -\text{lit-of } L) (\text{trail } S));$
 $W = \text{take } 2 (\text{negation-not-assigned } @ \text{negation-assigned-sorted-by-trail});$
 $UW = \text{sorted-list-of-multiset } (C - \text{mset } W)$
in *TWL-Clause* (*mset* W) (*mset* UW))

lemma *list-cases2*:
fixes $l :: 'a \text{ list}$
assumes
 $l = [] \implies P$ **and**
 $\bigwedge x. l = [x] \implies P$ **and**
 $\bigwedge x y xs. l = x \# y \# xs \implies P$
shows P
by (*metis assms list.collapse*)

lemma *filter-in-list-prop-verifiedD*:
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 *watch-nat-lists-disjointD*:
assumes
 $l: [L \leftarrow \text{remdups (sorted-list-of-set (set-mset } C \text{))} . - L \notin \text{lits-of (trail } S \text{)}] = l$ **and**
 $l': [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) (\text{trail } S) . L \in \# C] = l'$
shows $\forall x \in \text{set } l. \forall y \in \text{set } l'. x \neq y$
by (*auto simp*: $l[\text{symmetric}] l'[\text{symmetric}] \text{lits-of-def}$)

lemma *watch-nat-list-cases-witness*[*consumes 2*, *case-names nil-nil nil-single nil-other*

single-nil single-other other]:

fixes

$C :: 'v \text{ literal multiset}$ **and**

$C' :: 'v \text{ literal list}$ **and**

$S :: (('v, 'b, 'c) \text{ marked-lit}, 'd, 'e, 'f) \text{ twl-state}$

defines

$xs \equiv [L \leftarrow \text{remdups } C'. - L \notin \text{lits-of } (\text{trail } S)]$ **and**

$ys \equiv [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) (\text{trail } S) . L \in \# C]$

assumes

$n\text{-d}: \text{no-dup } (\text{trail } S)$ **and**

$C': \text{set } C' = \text{set-mset } C$ **and**

$\text{nil-nil}: xs = [] \implies ys = [] \implies P$ **and**

$\text{nil-single}:$

$\bigwedge a. xs = [] \implies ys = [a] \implies a \in \# C \implies P$ **and**

$\text{nil-other}: \bigwedge a \ b \ ys'. xs = [] \implies ys = a \# b \# ys' \implies a \neq b \implies P$ **and**

$\text{single-nil}: \bigwedge a. xs = [a] \implies ys = [] \implies P$ **and**

$\text{single-other}: \bigwedge a \ b \ ys'. xs = [a] \implies ys = b \# ys' \implies a \neq b \implies P$ **and**

$\text{other}: \bigwedge a \ b \ xs'. xs = a \# b \# xs' \implies a \neq b \implies P$

shows P

proof –

note $xs\text{-def}[simp]$ **and** $ys\text{-def}[simp]$

have $\text{dist: distinct } [L \leftarrow \text{remdups } C'. - L \notin \text{lits-of } (\text{trail } S)]$

by *auto*

then have $H: \bigwedge a \ xs. [L \leftarrow \text{remdups } C'. - L \notin \text{lits-of } (\text{trail } S)]$

$\neq a \# a \# xs$

by *force*

show *?thesis*

apply ($\text{cases } [L \leftarrow \text{remdups } C'. - L \notin \text{lits-of } (\text{trail } S)]$

rule: list-cases2;

$\text{cases } [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) (\text{trail } S) . L \in \# C]$ *rule: list-cases2)*

using *nil-nil* **apply** *simp*

using *nil-single* **apply** (*force dest: filter-in-list-prop-verifiedD*)

using *nil-other*

apply (*auto dest: filter-in-list-prop-verifiedD watch-nat-lists-disjointD*

no-dup-filter-diff[OF n-d] simp: H))

using *single-nil* **apply** *simp*

using *single-other C' xs-def ys-def* **apply** (*smt imageE image-eqI list.set-intros(1) lits-of-def*

mem-Collect-eq set-filter set-map uminus-of-uminus-id)

using *single-other C' unfolding xs-def ys-def* **apply** (*smt imageE image-eqI list.set-intros(1)*

lits-of-def mem-Collect-eq set-filter set-map uminus-of-uminus-id)

using *other xs-def ys-def* **by** (*metis H*)+

qed

lemma *watch-nat-list-cases* [*consumes 1, case-names nil-nil nil-single nil-other single-nil*

single-other other]:

fixes

$C :: 'v::\text{linorder literal multiset}$ **and**

$S :: (('v, 'b, 'c) \text{ marked-lit}, 'd, 'e, 'f) \text{ twl-state}$

defines

$xs \equiv [L \leftarrow \text{remdups } (\text{sorted-list-of-set } (\text{set-mset } C)) . - L \notin \text{lits-of } (\text{trail } S)]$ **and**

$ys \equiv [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) (\text{trail } S) . L \in \# C]$

assumes

$n\text{-d}: \text{no-dup } (\text{trail } S)$ **and**

$\text{nil-nil}: xs = [] \implies ys = [] \implies P$ **and**

$\text{nil-single}:$

$\bigwedge a. xs = [] \implies ys = [a] \implies a \in \# C \implies P$ **and**
nil-other: $\bigwedge a b ys'. xs = [] \implies ys = a \# b \# ys' \implies a \neq b \implies P$ **and**
single-nil: $\bigwedge a. xs = [a] \implies ys = [] \implies P$ **and**
single-other: $\bigwedge a b ys'. xs = [a] \implies ys = b \# ys' \implies a \neq b \implies P$ **and**
other: $\bigwedge a b xs'. xs = a \# b \# xs' \implies a \neq b \implies P$
shows P
using *watch-nat-list-cases-witness*[*OF* $n-d$, of *sorted-list-of-set* (*set-mset* C) C P]
nil-nil nil-single nil-other single-nil single-other other
unfolding *xs-def*[*symmetric*] *ys-def*[*symmetric*] **by** *auto*

lemma *watch-nat-lists-set-union-witness*:

fixes
 $C :: 'v$ *literal multiset* **and**
 $C' :: 'v$ *literal list* **and**
 $S :: (('v, 'b, 'c)$ *marked-lit*, $'d, 'e, 'f)$ *twl-state*
defines
 $xs \equiv [L \leftarrow \text{remdups } C'. - L \notin \text{lits-of } (\text{trail } S)]$ **and**
 $ys \equiv [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) (\text{trail } S) . L \in \# C]$
assumes $n-d$: *no-dup* (*trail* S) **and** C' : *set* $C' = \text{set-mset } C$
shows *set-mset* $C = \text{set } xs \cup \text{set } ys$
using $n-d$ C' *uminus-lit-swap* **unfolding** *xs-def* *ys-def* **by** (*auto simp: lits-of-def*)

lemma *watch-nat-lists-set-union*:

fixes
 $C :: 'v::\text{linorder}$ *literal multiset* **and**
 $S :: (('v, 'b, 'c)$ *marked-lit*, $'d, 'e, 'f)$ *twl-state*
defines
 $xs \equiv [L \leftarrow \text{remdups } (\text{sorted-list-of-set } (\text{set-mset } C)). - L \notin \text{lits-of } (\text{trail } S)]$ **and**
 $ys \equiv [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) (\text{trail } S) . L \in \# C]$
assumes $n-d$: *no-dup* (*trail* S)
shows *set-mset* $C = \text{set } xs \cup \text{set } ys$
using *watch-nat-lists-set-union-witness*[of S (*sorted-list-of-set* (*set-mset* C)) C , *OF* $n-d$]
sorted-list-of-set *xs-def* *ys-def* **by** *blast*

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*:

assumes *no-dup* (*trail* S)
shows *raw-clause* (*watch-nat* S C) = C
using *assms*
apply (*cases rule: watch-nat-list-cases*[*OF* *assms*(1), of C])
by (*auto dest: filter-in-list-prop-verifiedD simp: watch-nat-def Let-def*
mset-intersection-inclusion subseteq-mset-def)

lemma *set-mset-is-single-in-mset-is-single*:

set-mset $C = \{a\} \implies x \in \# C \implies x = a$
by *fastforce*

lemma *index-uminus-index-map-uminus*:

$-a \in \text{set } L \implies \text{index } L (-a) = \text{index } (\text{map } \text{uminus } L) (a::'a \text{ literal})$
by (*induction* L) *auto*

lemma *index-filter*:

$a \in \text{set } L \implies b \in \text{set } L \implies P a \implies P b \implies$
 $\text{index } L a \leq \text{index } L b \iff \text{index } (\text{filter } P L) a \leq \text{index } (\text{filter } P L) b$
by (*induction* L) *auto*

lemma *wf-watch-witness*:

fixes $C :: 'a \text{ literal multiset}$ **and** $C' :: 'a \text{ literal list}$ **and**

$S :: (('a, 'b, 'c) \text{ marked-lit}, 'd, 'e, 'f) \text{ twl-state}$

defines

$\text{ass: negation-not-assigned} \equiv \text{filter } (\lambda L. -L \notin \text{lits-of } (\text{trail } S)) (\text{remdups } C')$ **and**

$\text{tr: negation-assigned-sorted-by-trail} \equiv \text{filter } (\lambda L. L \in \# C) (\text{map } (\lambda L. -\text{lit-of } L) (\text{trail } S))$

defines

$W: W \equiv \text{take } 2 (\text{negation-not-assigned } @ \text{ negation-assigned-sorted-by-trail})$

assumes

$n\text{-d}[\text{simp}]: \text{no-dup } (\text{trail } S)$ **and**

$C': \text{set } C' = \text{set-mset } C$

shows $\text{wf-twlc} (\text{trail } S) (\text{TWL-Clause } (\text{mset } W) (C - \text{mset } W))$

unfolding wf-twlc.simps

proof (*intro conjI*, *goal-cases*)

case 1

then show ?case **using** $n\text{-d } C' W$ **unfolding** ass tr

by (*cases rule: watch-nat-list-cases-witness*[*of* $S C' C$])

(*auto dest: filter-in-list-prop-verifiedD*

simp: distinct-mset-add-single)

next

case 2

then show ?case **unfolding** W **by** *simp*

next

case 3

then show ?case **using** $n\text{-d } C'$

proof (*cases rule: watch-nat-list-cases-witness*[*of* $S C' C$])

case *nil-nil*

then have $\text{set-mset } C = \text{set } [] \cup \text{set } []$

using C' *watch-nat-lists-set-union-witness* $n\text{-d}$ **by** *metis*

then show ?thesis

by *simp*

next

case (*nil-single* a)

then show ?thesis

using *watch-nat-lists-set-union-witness*[*of* $S C' C$] $C' 3$

by (*auto dest!:* *arg-cong*[*of* - $[] \text{ set}$] *simp: W ass tr*)

next

case *nil-other*

then show ?thesis

using 3 **by** (*auto dest!:* *arg-cong*[*of* - $[] \text{ set}$] *simp: W ass tr*)

next

case *single-nil*

show ?thesis

using *watch-nat-lists-set-union-witness*[*of* $S C' C$] $C' 3 \text{ mset-leD}$

by (*auto simp: W ass tr single-nil*)

next

case *single-other*

then show ?thesis

using 3 **by** (*auto dest!:* *arg-cong*[*of* - $[] \text{ set}$] *simp: W ass tr*)

```

next
  case other
  then show ?thesis
    using 3 by (auto dest!: arg-cong[of - [] set] simp: W ass tr)
qed
next
case 4 note -[simp] = this
{
  fix a :: 'a literal and ys' :: 'a literal list and L :: 'a literal and
    L' :: 'a literal
  assume a1: [L←remdups C'. - L ∉ lits-of (trail S)] = [a]
  assume a2: set-mset C = insert L (insert a (set ys'))
  assume a3: L' ∈# C
  assume a4: a ≠ L'
  have set (L # a # ys') = set-mset C
    using a2 by auto
  then have L' ∉ set [l←remdups C'. - l ∉ lits-of (trail S)]
    using a4 a1 by (metis list.set(1) list.set(2) singleton-iff)
  then have - L' ∈ lits-of (trail S)
    using a3 C' by simp
  } note H = this
show ?case
using n-d C' apply (cases rule: watch-nat-list-cases-witness[of S C' C])
  apply (auto dest: filter-in-list-prop-verifiedD
    simp: W ass tr lits-of-def C' filter-empty-conv)[4]
using watch-nat-lists-set-union-witness[of S C' C] C'
  by (auto dest: filter-in-list-prop-verifiedD H simp: W ass tr)
next
case 5
from n-d C' show ?case
proof (cases rule: watch-nat-list-cases-witness[of S C' C])
  case nil-nil
  then show ?thesis by (auto simp: W ass tr)
next
  case nil-single
  then show ?thesis
    using watch-nat-lists-set-union-witness[of S C' C] C' by (auto simp: W ass tr)
next
  case nil-other
  then show ?thesis
    unfolding watched-decided-most-recently.simps Ball-mset-def
    apply (intro allI impI)
    apply (subst index-uminus-index-map-uminus,
      simp add: index-uminus-index-map-uminus lits-of-def o-def)
    apply (subst index-uminus-index-map-uminus,
      simp add: index-uminus-index-map-uminus lits-of-def o-def)

    apply (subst index-filter[of - - λL. L ∈# C])
    by (auto dest: filter-in-list-prop-verifiedD
      simp: uminus-lit-swap lits-of-def o-def W ass tr)
next
  case single-nil
  then show ?thesis
    using watch-nat-lists-set-union-witness[of S C' C] C' by (auto simp: W ass tr)
next

```



```

case single-other
then show ?thesis
  unfolding watched-decided-most-recently.simps Ball-mset-def
  apply (clarify)
  apply (subst index-uminus-index-map-uminus,
    simp add: index-uminus-index-map-uminus lits-of-def o-def)
  apply (subst index-uminus-index-map-uminus,
    simp add: index-uminus-index-map-uminus lits-of-def o-def)

  apply (subst index-filter[of - - λL. L ∈# C])
  by (auto dest: filter-in-list-prop-verifiedD
    simp: W ass tr uminus-lit-swap lits-of-def o-def)
next
case other
then show ?thesis
  unfolding watched-decided-most-recently.simps
  apply clarify
  apply (subst index-uminus-index-map-uminus,
    simp add: index-uminus-index-map-uminus lits-of-def o-def)[1]
  apply (subst index-uminus-index-map-uminus,
    simp add: index-uminus-index-map-uminus lits-of-def o-def)[1]

  apply (subst index-filter[of - - λL. L ∈# C])
  by (auto dest: filter-in-list-prop-verifiedD
    simp: index-uminus-index-map-uminus lits-of-def o-def uminus-lit-swap
    W ass tr)
qed
qed

lemma wf-watch-nat: no-dup (trail S) ⇒ wf-twl-cls (trail S) (watch-nat S C)
using wf-watch-witness[of S sorted-list-of-set (set-mset C) C]
by (metis List.finite-set mset-sorted-list-of-multiset set-sorted-list-of-multiset
  sorted-list-of-set watch-nat-def)

definition
  rewatch-nat ::
    (nat, nat, nat literal multiset) marked-lit ⇒ (nat, nat, nat clause) twl-state-abs ⇒
    nat clause twl-clause ⇒ nat clause twl-clause
where
  rewatch-nat L S C =
    (if - lit-of L ∈# watched C then
      case filter (λL'. L' ∉# watched C ∧ - L' ∉ lits-of (L # trail S))
        (sorted-list-of-multiset (unwatched C)) of
         $\square \Rightarrow C$ 
      | L' # - ⇒
        TWL-Clause (watched C - {#- lit-of L#} + {#L'#}) (unwatched C - {#L'#} + {#- lit-of
L#})
      else
        C)

lemma clause-rewatch-witness:
fixes UW :: 'a literal list and
  S :: (('a, 'b, 'c) marked-lit, 'd, 'e, 'f) twl-state and
  L :: ('a, 'b, 'c) marked-lit and C :: 'a literal multiset twl-clause
defines C' ≡ (if - lit-of L ∈# watched C then

```

```

    case filter (λL'. L' ∉ # watched C ∧ ¬ L' ∈ lits-of (L # trail S)) UW of
    | [] ⇒ C
    | L' # - ⇒
      TWL-Clause (watched C - {#- lit-of L#} + {#L'#}) (unwatched C - {#L'#} + {#- lit-of
L#})
    else
      C)
assumes
  UW: set UW = set-mset (unwatched C)
shows raw-clause C' = raw-clause C
using UW unfolding C'-def by (auto simp: subset-mset.add-diff-assoc2 multiset-eq-iff
split: list.split dest: filter-in-list-prop-verifiedD)

```

lemma clause-rewatch-nat: raw-clause (rewatch-nat L S C) = raw-clause C
using clause-rewatch-witness[of sorted-list-of-multiset (unwatched C) C - S]
by (auto simp: rewatch-nat-def Let-def split: list.split split-if-asm)

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-mempty:
 $a - \{ \#b\# \} = \{ \# \} \longleftrightarrow a = \{ \#b\# \} \vee a = \{ \# \}$
by (metis Multiset.diff-cancel add.right-neutral diff-single-eq-union
diff-single-trivial zero-diff)

lemma size-mset-le-2-cases:
assumes size W ≤ 2
shows W = {#} ∨ (∃ a. W = {#a#}) ∨ (∃ a b. W = {#a,b#})
by (metis One-nat-def Suc-1 Suc-eq-plus1-left assms linorder-not-less nat-less-le
not-less-eq-eq ordered-cancel-comm-monoid-diff-class.le-iff-add size-1-singleton-mset
size-eq-0-iff-empty size-mset-2)

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-witness':
fixes UWC :: 'a literal list **and**
 S :: (('a, 'b, 'c) marked-lit, 'd, 'e, 'f) twl-state **and**
 L :: ('a, 'b, 'c) marked-lit **and** C :: 'a literal multiset twl-clause
defines C' ≡ (if - lit-of L ∈ # watched C then

```

    case filter ( $\lambda L'. L' \notin \# \text{ watched } C \wedge - L' \notin \text{ lits-of } (L \# \text{ trail } S)$ )  $UWC$  of
    |  $\square \Rightarrow C$ 
    |  $L' \# - \Rightarrow$ 
       $TWL\text{-}Clause (\text{watched } C - \{\# - \text{ lit-of } L\} + \{\# L'\}) (\text{unwatched } C - \{\# L'\} + \{\# - \text{ lit-of } L\})$ 
    else
       $C$ )
  assumes
     $UWC$ :  $set \ UWC = set\text{-}mset \ (\text{unwatched } C)$  and
     $wf$ :  $wf\text{-}twl\text{-}cls \ (\text{trail } S) \ C$  and
     $n\text{-}d$ :  $no\text{-}dup \ (\text{trail } S)$  and
     $undef$ :  $undefined\text{-}lit \ (\text{trail } S) \ (\text{lit-of } L)$ 
  shows  $wf\text{-}twl\text{-}cls \ (L \# \text{ trail } S) \ C'$ 
proof (cases  $-\text{ lit-of } L \in \# \text{ watched } C$ )
  case False
  then have  $wf\text{-}twl\text{-}cls \ (L \# \text{ trail } S) \ C$ 
  apply (cases  $C$ )
  using  $wf \ n\text{-}d \ undef$  apply (clarify)
  unfolding  $wf\text{-}twl\text{-}cls.simps$ 
  apply (intro conjI)
    apply blast
    apply blast
    apply blast
  apply (smt ball-mset-cong bspec-mset insert-iff lits-of-cons nat-neq-iff twl-clause.sel(1)
    uminus-of-uminus-id)
  apply (auto simp: Marked-Propagated-in-iff-in-lits-of)
  done
  then show ?thesis
    using False  $C'\text{-def}$  by simp
next
  case falsified: True

  let ?unwatched-nonfalsified =
    [ $L' \leftarrow UWC. L' \notin \# \text{ watched } C \wedge - L' \notin \text{ lits-of } (L \# \text{ trail } S)$ ]
  obtain  $W \ UW$  where  $C$ :  $C = TWL\text{-}Clause \ W \ UW$ 
  by (cases  $C$ )

  show ?thesis
proof (cases ?unwatched-nonfalsified)
  case Nil
  show ?thesis
    using falsified Nil
    apply (simp only:  $wf\text{-}twl\text{-}cls.simps$  if-True list.cases  $C \ C'\text{-def}$ )
    apply (intro conjI)
  proof goal-cases
    case 1
    then show ?case using  $wf \ C$  by simp
  next
    case 2
    then show ?case using  $wf \ C$  by simp
  next
    case 3
    then show ?case using  $wf \ C$  by simp
  next
    case 4

```

```

have  $\bigwedge p l. \text{filter } p \text{ } UWC \neq [] \vee l \notin \text{set-mset } UW \vee \neg p l$ 
  using UWC unfolding C by (metis (no-types) filter-empty-conv twl-clause.sel(2))
then show ?case
  using 4(2) unfolding Ball-mset-def by (metis (lifting) mem-set-mset-iff twl-clause.sel(1))
next
case 5
then show ?case

  using C apply simp
  using wf by (smt ball-msetI bspec-mset not-gr0 uminus-of-uminus-id
    watched-decided-most-recently.simps wf-twl-cls.simps)
qed
next
case (Cons L' Ls)
show ?thesis
  unfolding rewatch-nat-def C'-def
  using falsified Cons
  apply (simp only: wf-twl-cls.simps if-True list.cases C)
  apply (intro conjI)
  proof goal-cases
    case 1
    have distinct-mset (watched (TWL-Clause W UW))
      using wf unfolding C by auto
    moreover have  $L' \notin \# \text{watched } (TWL\text{-Clause } W \text{ } UW) - \{\# - \text{lit-of } L\# \}$ 
      using 1(2) not-gr0 by (fastforce dest: filter-in-list-prop-verifiedD)
    ultimately show ?case
      by (auto simp: distinct-mset-single-add)
  next
  case 2
  then show ?case using wf C by (metis insert-DiffM2 size-single size-union twl-clause.sel(1)
    wf-twl-cls.simps)
  next
  case 3
  then show ?case
    using wf C UWC by (force simp: mset-minus-single-eq-mempty dest: subset-singletonD)
  next
  case 4
  have  $H: \forall L \in \# W. - L \in \text{lits-of } (\text{trail } S) \longrightarrow$ 
     $(\forall L' \in \# UW. \text{count } W \text{ } L' = 0 \longrightarrow - L' \in \text{lits-of } (\text{trail } S))$ 
    using wf by (auto simp: C)
  have  $W: \text{size } W \leq 2 \text{ and } W-UW: \text{size } W < 2 \longrightarrow \text{set-mset } UW \subseteq \text{set-mset } W$ 
    using wf by (auto simp: C)

  have distinct: distinct-mset W
    using wf by (auto simp: C)
  show ?case
    using 4
    unfolding C watched-decided-most-recently.simps Ball-mset-def twl-clause.sel
    apply (intro allI impI)
    apply (rename-tac xW xUW)
    apply (case-tac  $-\text{lit-of } L = xW; \text{case-tac } xW = xUW; \text{case-tac } L' = xW$ )
      apply (auto simp: uminus-lit-swap)[2]
      apply (force dest: filter-in-list-prop-verifiedD)
    using H size-mset-le-2-cases[OF W]
    using distinct apply (fastforce split: split-if-asm simp: distinct-mset-size-2)

```

```

    using distinct apply (fastforce split: split-if-asm simp: distinct-mset-size-2)
    using distinct apply (fastforce split: split-if-asm simp: distinct-mset-size-2)
    apply (force dest: filter-in-list-prop-verifiedD)
    using size-mset-le-2-cases[OF W] H by (fastforce simp: uminus-lit-swap
    dest: filter-sorted-list-of-multiset-ConsD filter-sorted-list-of-multiset-eqD)

next
case 5
have H:  $\forall x. x \in \# W \longrightarrow - x \in \text{ lits-of } (\text{trail } S) \longrightarrow (\forall x. x \in \# UW \longrightarrow \text{count } W x = 0$ 
 $\longrightarrow - x \in \text{ lits-of } (\text{trail } S))$ 
using wf by (auto simp: C)

show ?case
using 5 unfolding C watched-decided-most-recently.simps Ball-mset-def
apply (intro allI impI conjI)
apply (rename-tac xW x)
apply (case-tac - lit-of L = xW; case-tac xW = x)
    apply (auto simp: uminus-lit-swap)[3]
apply (case-tac - lit-of L = x)
using H UWC C apply (force dest!: filter-in-list-prop-verifiedD)

apply (clarsimp)
using H C UWC by (metis (mono-tags, lifting) filter-in-list-prop-verifiedD
list.set-intros(1) mem-Collect-eq set-mset-def twl-clause.sel(2))
qed
qed
qed

lemma wf-rewatch-nat':
assumes
  wf: wf-twl-cls (trail S) C and
  n-d: no-dup (trail S) and
  undef: undefined-lit (trail S) (lit-of L)
shows wf-twl-cls (L # trail S) (rewatch-nat L S C)
using clause-rewatch-witness'[of sorted-list-of-multiset (unwatched C) C S L]
assms by (auto simp: rewatch-nat-def)

```

```

interpretation twl: 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)
done

```

21.5 Interpretation for $cdcl_W.cdcl_W$

```

context abstract-twl
begin

```

21.5.1 Direct Interpretation

```

interpretation rough-cdcl: 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)
apply (rule image-mset-subseteq-mono[OF restart-learned])
done

```

interpretation *rough-cdcl*: $cdcl_W$ 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'
by unfold-locales

interpretation $cdcl_{NOT}$: $cdcl_{NOT}$ -merge-bj-learn-ops
 $\lambda S.$ convert-trail-from- W (trail S)
rough-cdcl.clauses
 $\lambda L S.$ cons-trail (convert-marked-lit-from- NOT L) S
 $\lambda S.$ tl-trail S
 $\lambda C S.$ add-learned-cls $C S$
 $\lambda C S.$ remove-cls $C S$
 $\lambda L S.$ lit-of $L \in fst$ ' candidates-propagate S
 $\lambda S.$ conflicting $S = None$
 $\lambda C C' L' S.$ $C \in candidates-conflict S \wedge distinct-mset (C' + \{\#L'\# \}) \wedge \neg tautology (C' + \{\#L'\# \})$
by unfold-locales

21.5.2 Opaque Type with Invariant

declare *rough-cdcl.state-simp*[simp del]

definition *cons-trail-tw*l :: ('v, nat, 'v literal multiset) marked-lit \Rightarrow 'v wf-tw $l \Rightarrow$ 'v wf-tw l
where
*cons-trail-tw*l $L S \equiv twl\text{-of-rough-state } (cons\text{-trail } L (rough\text{-state-of-tw}l S))$

lemma *wf-tw*l-state-cons-trail:
 undefined-lit (trail S) (lit-of L) $\implies wf\text{-tw}l\text{-state } S \implies wf\text{-tw}l\text{-state } (cons\text{-trail } L S)$
unfolding *wf-tw*l-state-def **by** (auto simp: cons-trail-def wf-rewatch defined-lit-map)

lemma *rough-state-of-tw*l-cons-trail:
 undefined-lit (trail-tw $l S$) (lit-of L) \implies
 $rough\text{-state-of-tw}l (cons\text{-trail-tw}l L S) = cons\text{-trail } L (rough\text{-state-of-tw}l S)$
using *rough-state-of-tw*l twl-of-rough-state-inverse wf-tw l -state-cons-trail
unfolding *cons-trail-tw*l-def **by** blast

abbreviation *add-init-cl*s-tw l **where**
 $add\text{-init-cl} s\text{-tw}l C S \equiv twl\text{-of-rough-state } (add\text{-init-cl} s C (rough\text{-state-of-tw}l S))$

lemma *wf-tw*l-add-init-cl s : $wf\text{-tw}l\text{-state } S \implies wf\text{-tw}l\text{-state } (add\text{-init-cl} s L S)$
unfolding *wf-tw*l-state-def **by** (auto simp: wf-watch add-init-cl s -def split: split-if-asm)

lemma *rough-state-of-tw*l-add-init-cl s :
 $rough\text{-state-of-tw}l (add\text{-init-cl} s\text{-tw}l L S) = add\text{-init-cl} s L (rough\text{-state-of-tw}l S)$
using *rough-state-of-tw*l twl-of-rough-state-inverse wf-tw l -add-init-cl s **by** blast

abbreviation *add-learned-cl*s-tw l **where**
 $add\text{-learned-cl} s\text{-tw}l C S \equiv twl\text{-of-rough-state } (add\text{-learned-cl} s C (rough\text{-state-of-tw}l S))$

lemma *wf-twl-add-learned-cls*: $wf\text{-}twl\text{-}state\ S \implies wf\text{-}twl\text{-}state\ (add\text{-}learned\text{-}cls\ L\ S)$
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*:
 $rough\text{-}state\text{-}of\text{-}twl\ (add\text{-}learned\text{-}cls\text{-}twl\ L\ S) = add\text{-}learned\text{-}cls\ L\ (rough\text{-}state\text{-}of\text{-}twl\ S)$
using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-add-learned-cls* **by** *blast*

abbreviation *remove-cls-twl* **where**
 $remove\text{-}cls\text{-}twl\ C\ S \equiv twl\text{-}of\text{-}rough\text{-}state\ (remove\text{-}cls\ C\ (rough\text{-}state\text{-}of\text{-}twl\ S))$

lemma *wf-twl-remove-cls*: $wf\text{-}twl\text{-}state\ S \implies wf\text{-}twl\text{-}state\ (remove\text{-}cls\ L\ S)$
unfolding *wf-twl-state-def* **by** (*auto simp*: *wf-watch remove-cls-def split: split-if-asm*)

lemma *rough-state-of-twl-remove-cls*:
 $rough\text{-}state\text{-}of\text{-}twl\ (remove\text{-}cls\text{-}twl\ L\ S) = remove\text{-}cls\ L\ (rough\text{-}state\text{-}of\text{-}twl\ S)$
using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-remove-cls* **by** *blast*

abbreviation *init-state-twl* **where**
 $init\text{-}state\text{-}twl\ N \equiv twl\text{-}of\text{-}rough\text{-}state\ (init\text{-}state\ N)$

lemma *wf-twl-state-wf-twl-state-fold-add-init-cls*:
assumes *wf-twl-state* *S*
shows $wf\text{-}twl\text{-}state\ (fold\ add\text{-}init\text{-}cls\ N\ S)$
using *assms apply* (*induction N arbitrary: S*)
apply (*auto simp*: *wf-twl-state-def*)
by (*simp add: wf-twl-add-init-cls*)

lemma *wf-twl-state-epsilon-state[simp]*:
 $wf\text{-}twl\text{-}state\ (TWL\text{-}State\ []\ \{\#\}\ \{\#\}\ 0\ None)$
by (*auto simp*: *wf-twl-state-def*)

lemma *wf-twl-init-state*: $wf\text{-}twl\text{-}state\ (init\text{-}state\ N)$
unfolding *init-state-def* **by** (*auto intro!*: *wf-twl-state-wf-twl-state-fold-add-init-cls*)

lemma *rough-state-of-twl-init-state*:
 $rough\text{-}state\text{-}of\text{-}twl\ (init\text{-}state\text{-}twl\ N) = init\text{-}state\ N$
by (*simp add: twl-of-rough-state-inverse wf-twl-init-state*)

abbreviation *tl-trail-twl* **where**
 $tl\text{-}trail\text{-}twl\ S \equiv twl\text{-}of\text{-}rough\text{-}state\ (tl\text{-}trail\ (rough\text{-}state\text{-}of\text{-}twl\ S))$

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*

lemma *rough-state-of-twl-update-backtrack-lvl*:
 $\text{rough-state-of-twl } (\text{update-backtrack-lvl-twl } k \ S) = \text{update-backtrack-lvl } k$
 $(\text{rough-state-of-twl } S)$
using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-state-update-backtrack-lvl* **by** *fast*

abbreviation *update-conflicting-twl* **where**
 $\text{update-conflicting-twl } k \ S \equiv \text{twl-of-rough-state } (\text{update-conflicting } k \ (\text{rough-state-of-twl } S))$

lemma *wf-twl-state-update-conflicting*:
 $\text{wf-twl-state } S \implies \text{wf-twl-state } (\text{update-conflicting } k \ S)$
unfolding *wf-twl-state-def* **by** *auto*

lemma *rough-state-of-twl-update-conflicting*:
 $\text{rough-state-of-twl } (\text{update-conflicting-twl } k \ S) = \text{update-conflicting } k$
 $(\text{rough-state-of-twl } S)$
using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-state-update-conflicting* **by** *fast*

abbreviation *raw-clauses-twl* **where**
 $\text{raw-clauses-twl } S \equiv \text{raw-clauses } (\text{rough-state-of-twl } S)$

abbreviation *restart-twl* **where**
 $\text{restart-twl } S \equiv \text{twl-of-rough-state } (\text{restart}' \ (\text{rough-state-of-twl } S))$

lemma *wf-wf-restart'*: $\text{wf-twl-state } S \implies \text{wf-twl-state } (\text{restart}' \ S)$
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*:
 $\text{rough-state-of-twl } (\text{restart-twl } S) = \text{restart}' \ (\text{rough-state-of-twl } S)$
by *(simp add: twl-of-rough-state-inverse wf-wf-restart')*

interpretation *cdcl_W-twl-NOT*: *dpll-state*
 $\lambda S. \text{convert-trail-from-}W \ (\text{trail-twl } S)$
 raw-clauses-twl
 $\lambda L \ S. \text{cons-trail-twl } (\text{convert-marked-lit-from-NOT } L) \ S$
 $\lambda S. \text{tl-trail-twl } S$
 $\lambda C \ S. \text{add-learned-cls-twl } C \ S$
 $\lambda C \ S. \text{remove-cls-twl } C \ S$
apply *unfold-locales*
apply *(simp add: rough-state-of-twl-cons-trail)*
apply *(metis rough-state-of-twl-tl-trail rough-cdcl.tl-trail)*
apply *(metis rough-state-of-twl-add-learned-cls rough-cdcl.trail-add-cls_{NOT})*
apply *(metis rough-state-of-twl-remove-cls rough-cdcl.trail-remove-cls)*
apply *(simp add: rough-state-of-twl-cons-trail)*
apply *(simp add: twl.rough-state-of-twl-tl-trail)*
using *rough-cdcl.clauses-add-cls_{NOT} rough-cdcl.clauses-def rough-state-of-twl-add-learned-cls*
apply *auto[1]*
using *rough-cdcl.clauses-def rough-cdcl.clauses-remove-cls rough-state-of-twl-remove-cls* **by** *auto*

interpretation $cdcl_W\text{-twl}$: $state_W$

trail-tw
init-clss-tw
learned-clss-tw
backtrack-lvl-tw
conflicting-tw
cons-trail-tw
tl-trail-tw
add-init-cls-tw
add-learned-cls-tw
remove-cls-tw
update-backtrack-lvl-tw
update-conflicting-tw
init-state-tw
restart-tw

apply *unfold-locales*

by (*simp-all add: rough-state-of-tw-cons-trail rough-state-of-tw-tl-trail*
rough-state-of-tw-add-init-cls rough-state-of-tw-add-learned-cls rough-state-of-tw-remove-cls
rough-state-of-tw-update-backtrack-lvl rough-state-of-tw-update-conflicting
rough-state-of-tw-init-state rough-state-of-tw-restart-tw
rough-cdcl.learned-clss-restart-state)

interpretation $cdcl_W\text{-twl}$: $cdcl_W$

trail-tw
init-clss-tw
learned-clss-tw
backtrack-lvl-tw
conflicting-tw
cons-trail-tw
tl-trail-tw
add-init-cls-tw
add-learned-cls-tw
remove-cls-tw
update-backtrack-lvl-tw
update-conflicting-tw
init-state-tw
restart-tw

by *unfold-locales*

abbreviation *state-eq-tw* (**infix** $\sim TWL$ 51) **where**

state-eq-tw $S S' \equiv \text{rough-cdcl.state-eq } (\text{rough-state-of-tw } S) (\text{rough-state-of-tw } S')$

notation $cdcl_W\text{-twl.state-eq}$ (**infix** \sim 51)

declare $cdcl_W\text{-twl.state-simp}$ [*simp del*]

$cdcl_W\text{-twl.NOT.state-simp}_{NOT}$ [*simp del*]

To avoid ambiguities:

no-notation *CDCL-Two-Watched-Literals.twl.state-eq-tw* (**infix** $\sim TWL$ 51)

definition *propagate-tw* **where**

propagate-tw $S S' \longleftrightarrow$

($\exists L C. (L, C) \in \text{candidates-propagate-tw } S$
 $\wedge S' \sim TWL \text{ cons-trail-tw } (\text{Propagated } L C) S$
 $\wedge \text{conflicting-tw } S = \text{None}$)

lemma *propagate-tw-iff-propagate*:

assumes *inv*: $cdcl_W\text{-}twl.cdcl_W\text{-}all\text{-}struct\text{-}inv\ S$
shows $cdcl_W\text{-}twl.propagate\ S\ T \longleftrightarrow propagate\text{-}twl\ S\ T$ (**is** $?P \longleftrightarrow ?T$)
proof
assume $?P$
then obtain $C\ L$ **where**
conflicting (*rough-state-of-twl* S) = *None* **and**
CL-Clauses: $C + \{\#L\# \} \in \# cdcl_W\text{-}twl.clauses\ S$ **and**
tr-CNot: $trail\text{-}twl\ S \models_{as} CNot\ C$ **and**
undef-lot: *undefined-lit* (*trail-twl* S) L **and**
 $T \sim cons\text{-}trail\text{-}twl\ (Propagated\ L\ (C + \{\#L\# \}))\ S$
unfolding $cdcl_W\text{-}twl.propagate.simps$ **by** *blast*
have *distinct-mset* ($C + \{\#L\# \}$)
using *inv* *CL-Clauses* **unfolding** $cdcl_W\text{-}twl.cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def$
 $cdcl_W\text{-}twl.distinct\text{-}cdcl_W\text{-}state\text{-}def\ cdcl_W\text{-}twl.clauses\text{-}def\ distinct\text{-}mset\text{-}set\text{-}def$
by (*metis* (*no-types*, *lifting*) *add-gr-0* *mem-set-mset-iff* *plus-multiset.rep-eq*)
then have $C\text{-}L\text{-}L$: *mset-set* (*set-mset* ($C + \{\#L\# \}$) - $\{L\}$) = C
by (*metis* *Un-insert-right* *add-diff-cancel-left'* *add-diff-cancel-right'*
distinct-mset-set-mset-ident *finite-set-mset* *insert-absorb2* *mset-set.insert-remove*
set-mset-single *set-mset-union*)
have ($L, C + \{\#L\# \}$) $\in candidates\text{-}propagate\text{-}twl\ S$
apply (*rule* *wf-candidates-propagate-complete*)
using *rough-state-of-twl* **apply** *auto*[]
using *CL-Clauses* **unfolding** $cdcl_W\text{-}twl.clauses\text{-}def$ **apply** *auto*[]
apply *simp*
using $C\text{-}L\text{-}L$ *tr-CNot* **apply** *simp*
using *undef-lot* **apply** *blast*
done
show $?T$ **unfolding** *propagate-twl-def*
apply (*rule* *exI*[*of* - L], *rule* *exI*[*of* - $C + \{\#L\# \}$])
apply (*auto* *simp*: $\langle (L, C + \{\#L\# \}) \in candidates\text{-}propagate\text{-}twl\ S \rangle$
 $\langle conflicting\ (rough\text{-}state\text{-}of\text{-}twl\ S) = None \rangle$)
using $\langle T \sim cons\text{-}trail\text{-}twl\ (Propagated\ L\ (C + \{\#L\# \}))\ S \rangle\ cdcl_W\text{-}twl.state\text{-}eq\text{-}backtrack\text{-}lvl$
 $cdcl_W\text{-}twl.state\text{-}eq\text{-}conflicting\ cdcl_W\text{-}twl.state\text{-}eq\text{-}init\text{-}clss$
 $cdcl_W\text{-}twl.state\text{-}eq\text{-}learned\text{-}clss\ cdcl_W\text{-}twl.state\text{-}eq\text{-}trail\ rough\text{-}cdcl.state\text{-}eq\text{-}def$ **by** *blast*
next
assume $?T$
then obtain $L\ C$ **where**
 LC : $(L, C) \in candidates\text{-}propagate\text{-}twl\ S$ **and**
 T : $T \sim TWL\ cons\text{-}trail\text{-}twl\ (Propagated\ L\ C)\ S$ **and**
cnfl: *conflicting* (*rough-state-of-twl* S) = *None*
unfolding *propagate-twl-def* **by** *auto*
have [*simp*]: $C - \{\#L\# \} + \{\#L\# \} = C$
using LC **unfolding** *candidates-propagate-def*
by *clarify* (*metis* *add.commute* *add-diff-cancel-right'* *count-diff* *insert-DiffM*
multi-member-last *not-gr0* *zero-diff*)
have $C \in \# raw\text{-}clauses\text{-}twl\ S$
using LC **unfolding** *candidates-propagate-def* *rough-cdcl.clauses-def* **by** *auto*
then have *distinct-mset* C
using *inv* **unfolding** $cdcl_W\text{-}twl.cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def\ cdcl_W\text{-}twl.distinct\text{-}cdcl_W\text{-}state\text{-}def$
 $cdcl_W\text{-}twl.clauses\text{-}def\ distinct\text{-}mset\text{-}set\text{-}def\ rough\text{-}cdcl.clauses\text{-}def$ **by** *auto*
then have $C\text{-}L\text{-}L$: *mset-set* (*set-mset* $C - \{L\}$) = $C - \{\#L\# \}$
by (*metis* $\langle C - \{\#L\# \} + \{\#L\# \} = C \rangle$ *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 cdclW-twl.propagate.intros[of - trail-twl S init-clss-twl S
    learned-clss-twl S backtrack-lvl-twl S C-{\#L\#} L])
    using confl apply auto[]
    using LC unfolding candidates-propagate-def apply (auto simp: cdclW-twl.clauses-def)[]
    using wf-candidates-propagate-sound[OF - LC] rough-state-of-twl apply (simp add: C-L-L)
    using wf-candidates-propagate-sound[OF - LC] rough-state-of-twl apply simp
    using T unfolding cdclW-twl.state-eq-def rough-cdcl.state-eq-def by auto
qed

term local.state-eq-twl
term CDCL-Two-Watched-Literals.twl.state-eq-twl
definition conflict-twl where
  conflict-twl S S'  $\longleftrightarrow$ 
    ( $\exists C. C \in \text{candidates-conflict-twl } S$ 
 $\wedge S' \sim \text{TWL update-conflicting-twl (Some } C) S$ 
 $\wedge \text{conflicting-twl } S = \text{None}$ )

lemma conflict-twl-iff-conflict:
  shows cdclW-twl.conflict S T  $\longleftrightarrow$  conflict-twl S T (is ?C  $\longleftrightarrow$  ?T)
proof
  assume ?C
  then obtain M N U k C where
    S: rough-cdcl.state (rough-state-of-twl S) = (M, N, U, k, None) and
    C: C  $\in \#$  cdclW-twl.clauses S and
    M-C: M  $\models_{\text{as}}$  CNot C and
    T: T  $\sim$  update-conflicting-twl (Some C) S
    by auto
  have C  $\in$  candidates-conflict-twl S
    apply (rule wf-candidates-conflict-complete)
    apply simp
    using C apply (auto simp: cdclW-twl.clauses-def)[]
    using M-C S by auto
  moreover have T  $\sim$  TWL twl-of-rough-state (update-conflicting (Some C) (rough-state-of-twl S))
    using T unfolding rough-cdcl.state-eq-def cdclW-twl.state-eq-def by auto
  ultimately show ?T
    using S unfolding conflict-twl-def by auto
next
  assume ?T
  then obtain C where
    C: C  $\in$  candidates-conflict-twl S and
    T: T  $\sim$  TWL update-conflicting-twl (Some C) S and
    confl: conflicting-twl S = None
    unfolding conflict-twl-def by auto
  have C  $\in \#$  cdclW-twl.clauses S
    using C unfolding candidates-conflict-def cdclW-twl.clauses-def by auto
  moreover have trail-twl S  $\models_{\text{as}}$  CNot C
    using wf-candidates-conflict-sound[OF - C] by auto
  ultimately show ?C apply -
    apply (rule cdclW-twl.conflict.conflict-rule[of - - - - C])
    using confl T unfolding rough-cdcl.state-eq-def cdclW-twl.state-eq-def by auto
qed

inductive cdclW-twl :: 'v wf-twl  $\Rightarrow$  'v wf-twl  $\Rightarrow$  bool for S :: 'v wf-twl where
  propagate: propagate-twl S S'  $\Longrightarrow$  cdclW-twl S S' |

```

conflict: $\text{conflict-twl } S \ S' \implies \text{cdcl}_W\text{-twl } S \ S' \mid$
other: $\text{cdcl}_W\text{-twl.cdcl}_W\text{-o } S \ S' \implies \text{cdcl}_W\text{-twl } S \ S' \mid$
rf: $\text{cdcl}_W\text{-twl.cdcl}_W\text{-rf } S \ S' \implies \text{cdcl}_W\text{-twl } S \ S'$

lemma *cdcl_W-twl-iff-cdcl_W*:

assumes *cdcl_W-twl.cdcl_W-all-struct-inv S*

shows *cdcl_W-twl S T \longleftrightarrow cdcl_W-twl.cdcl_W S T*

by (*simp add: assms cdcl_W-twl.cdcl_W.simps cdcl_W-twl.simps conflict-twl-iff-conflict propagate-twl-iff-propagate*)

lemma *rtrancpl-cdcl_W-twl-all-struct-inv-inv*:

assumes *cdcl_W-twl** S T and cdcl_W-twl.cdcl_W-all-struct-inv S*

shows *cdcl_W-twl.cdcl_W-all-struct-inv T*

using *assms by (induction rule: rtrancpl-induct)*

(*simp-all add: cdcl_W-twl-iff-cdcl_W cdcl_W-twl.cdcl_W-all-struct-inv-inv*)

lemma *rtrancpl-cdcl_W-twl-iff-rtrancpl-cdcl_W*:

assumes *cdcl_W-twl.cdcl_W-all-struct-inv S*

shows *cdcl_W-twl** S T \longleftrightarrow cdcl_W-twl.cdcl_W** S T (is ?T \longleftrightarrow ?W)*

proof

assume *?W*

then show *?T*

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 *cdcl_W-twl T U*

using *assms st cdcl cdcl_W-twl.rtrancpl-cdcl_W-all-struct-inv-inv cdcl_W-twl-iff-cdcl_W*

by *blast*

then show *?case using IH by auto*

qed

next

assume *?T*

then show *?W*

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 *cdcl_W-twl.cdcl_W T U*

using *assms st cdcl rtrancpl-cdcl_W-twl-all-struct-inv-inv cdcl_W-twl-iff-cdcl_W*

by *blast*

then show *?case using IH by auto*

qed

qed

interpretation *cdcl_{NOT}-twl: backjumping-ops*

λS. convert-trail-from-W (trail-twl S)

abstract-twl.raw-clauses-twl

λL (S:: 'v wf-twl).

cons-trail-twl

(convert-marked-lit-from-NOT L) (S:: 'v wf-twl)

tl-trail-twl

add-learned-cls-twl

remove-cls-twl
 $\lambda C \text{ - - } (S :: 'v \text{ wf-twl}) \text{ - . } C \in \text{candidates-conflict-twl } S$
by *unfold-locales*

lemma *reduce-trail-to_{NOT}-skip-beginning-twl*:
assumes *trail-twl* $S = \text{convert-trail-from-NOT } (F' @ F)$
shows *trail-twl* $(\text{cdcl}_W\text{-twl.reduce-trail-to}_{NOT} F S) = \text{convert-trail-from-NOT } F$
using *assms* **by** (*induction* F' *arbitrary*: S) *auto*

lemma *reduce-trail-to_{NOT}-trail-tl-trail-twl-decomp[simp]*:
 $\text{trail-twl } S = \text{convert-trail-from-NOT } (F' @ \text{Marked } K () \# F) \implies$
 $\text{trail-twl } (\text{cdcl}_W\text{-twl.reduce-trail-to}_{NOT} F (\text{tl-trail-twl } S)) = \text{convert-trail-from-NOT } F$
apply (*rule* *reduce-trail-to_{NOT}-skip-beginning-twl*[*of* - *tl* $(F' @ \text{Marked } K () \# [])$])
by (*cases* F') (*auto simp add:tl-append rough-cdcl.reduce-trail-to_{NOT}-skip-beginning*)

lemma *trail-twl-reduce-trail-to_{NOT}-drop*:
 $\text{trail-twl } (\text{cdcl}_W\text{-twl.reduce-trail-to}_{NOT} F S) =$
 (*if* *length* $(\text{trail-twl } S) \geq \text{length } F$
then *drop* $(\text{length } (\text{trail-twl } S) - \text{length } F)$ $(\text{trail-twl } S)$
else $[]$)
apply (*induction* $F S$ *rule*: *cdcl_W-twl.reduce-trail-to_{NOT}.induct*)
apply (*rename-tac* $F S$)
apply (*case-tac* *trail-twl* S)
apply *auto*
apply (*rename-tac* *list*)
apply (*case-tac* *Suc* $(\text{length } \text{list}) > \text{length } F$)
prefer 2 **apply** *simp*
apply (*subgoal-tac* *Suc* $(\text{length } \text{list}) - \text{length } F = \text{Suc } (\text{length } \text{list} - \text{length } F)$)
apply *simp*
apply *simp*
done

interpretation *cdcl_{NOT}-twl*: *dpll-with-backjumping-ops*

$\lambda S. \text{convert-trail-from-} W (\text{trail-twl } S)$

abstract-twl.raw-clauses-twl

$\lambda L. S.$

cons-trail-twl

$(\text{convert-marked-lit-from-NOT } L) S$

tl-trail-twl

add-learned-cls-twl

remove-cls-twl

$\lambda L. S. \text{lit-of } L \in \text{fst 'candidates-propagate-twl } S$

$\lambda S. \text{no-dup } (\text{trail-twl } S)$

$\lambda C \text{ - - } S \text{ - . } C \in \text{candidates-conflict-twl } S$

proof (*unfold-locales*, *goal-cases*)

case $(1 \ C' S C F' K F L)$ **note** $n\text{-d} = \text{this}(1)$ **and** $n\text{-d}' = \text{this}(2)$ **and** $\text{undef} = \text{this}(6)$

let $?T' = (\text{cons-trail } (\text{Propagated } L \ \{\#\}) (\text{rough-state-of-twl } (\text{cdcl}_W\text{-twl.reduce-trail-to}_{NOT} F S)))$

let $?T = (\text{cons-trail-twl } (\text{Propagated } L \ \{\#\}) (\text{cdcl}_W\text{-twl.reduce-trail-to}_{NOT} F S))$

have *tr-F-S*: $\text{map lit-of } (\text{trail-twl } (\text{cdcl}_W\text{-twl.reduce-trail-to}_{NOT} F S)) =$

$\text{map lit-of } (\text{convert-trail-from-NOT } F)$

apply (*subst* *trail-twl-reduce-trail-to_{NOT}-drop*[*of* $F S$])

using $1(1)$ *arg-cong*[*OF* $1(3)$, *of* *length*] *arg-cong*[*OF* $1(3)$, *of* *map lit-of*]

by (*auto simp: o-def drop-map[symmetric]*)

have *no-dup* $(\text{trail-twl } S)$

```

    using 1(1) by blast
have wf-twl-state (rough-state-of-twl (cdclW-twl.reduce-trail-toNOT F S))
  using wf-twl-state-rough-state-of-twl by blast
moreover have undef': undefined-lit (trail-twl (cdclW-twl.reduce-trail-toNOT F S)) L
  using undef arg-cong[OF tr-F-S, of map atm-of] unfolding defined-lit-map image-set
  by (simp add: o-def)
ultimately have wf-twl-state ?T'
  by (simp-all add: wf-twl-state-cons-trail)
then have init-clss-twl ?T = init-clss-twl (cdclW-twl.reduce-trail-toNOT F S)
  using 1(6) by (simp add: undef')
then have [simp]: init-clss-twl ?T = init-clss-twl S
  by (simp add: cdclW-twl.reduce-trail-toNOT-reduce-trail-convert)

have learned-clss-twl ?T = learned-clss-twl (cdclW-twl.reduce-trail-toNOT F S)
  by (smt 1(3) 1(6) append-assoc cdclW-twl.learned-clss-cons-trail
      cdclW-twl-NOT.reduce-trail-toNOT-eq-length cdclW-twl-NOT.reduce-trail-toNOT-nil
      cdclW-twl-NOT.reduce-trail-toNOT-skip-beginning comp-apply defined-lit-convert-trail-from-W
      list.sel(3) marked-lit.sel(2) rev.simps(2) rev-append rev-eq-Cons-iff
      cons-trail-twl-def)
moreover have learned-clss-twl (cdclW-twl.reduce-trail-toNOT F S)
  = learned-clss-twl S
  by (simp add: cdclW-twl.reduce-trail-toNOT-reduce-trail-convert)
ultimately have [simp]: learned-clss-twl ?T = learned-clss-twl S
  by simp
have tr-L-F-S: map lit-of (trail-twl ?T)
  = map lit-of (Propagated L {#} # convert-trail-from-NOT F)
  using undef' tr-F-S by (simp add: o-def)
have C-conflict-cand: C ∈ candidates-conflict-twl S
  apply (rule wf-candidates-twl-conflict-complete)
  using 1(1,4) apply (simp add: rough-cdcl.clauses-def)
  using 1(5) by (simp add: tr-L-F-S true-annots-true-cls lits-of-convert-trail-from-NOT)

have cdclNOT-twl.backjump S
  (cons-trail-twl (convert-marked-lit-from-NOT (Propagated L ()))
   (cdclW-twl.reduce-trail-toNOT F S))
  apply (rule cdclNOT-twl.backjump.intros[of S F' K F - L C, OF 1(3) - 1(4-6) - 1(8-9)])
  unfolding cdclW-twl-NOT.state-eqNOT-def apply (metis convert-marked-lit-from-NOT.simps(1))
  using 1(7) 1(3) apply presburger
  using C-conflict-cand by simp
then show ?case
  by blast
qed

interpretation cdclNOT-twl: dp11-with-backjumping
λS. convert-trail-from-W (trail-twl S)
abstract-twl.raw-clauses-twl
λL (S:: 'v wf-twl).
  cons-trail-twl
    (convert-marked-lit-from-NOT L) (S:: 'v wf-twl)
tl-trail-twl
add-learned-cls-twl
remove-cls-twl
λL S. lit-of L ∈ fst ' candidates-propagate-twl S
λS. no-dup (trail-twl S)
λC - - (S:: 'v wf-twl) -. C ∈ candidates-conflict-twl S

```

```

apply unfold-locals
using cdclNOT.twl.dpll-bj-no-dup by (simp add: o-def)
end

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 ( $\prec^{\sup}$   $\succ^{\sup}$ )

locale selection =
  fixes S :: 'a clause  $\Rightarrow$  'a clause
  assumes
    S-selects-subseteq:  $\bigwedge C. S\ C \leq \# C$  and
    S-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 $C =$

$\{A. C \in N \wedge C \neq \{\#\} \wedge \text{Max}(\text{set-mset } C) = \text{Pos } A \wedge \text{count } C (\text{Pos } A) \leq 1$
 $\wedge \neg (\bigcup D \in \{D. D \# \subset \# C\}. \text{production } D) \models_h C \wedge S C = \{\#\}\}$

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 $C = (\bigcup D \in \{D. D \# \subset \# C\}. \text{production } D)$

lemma *production-unfold*:

production $C = \{A. C \in N \wedge C \neq \{\#\} \wedge \text{Max}(\text{set-mset } C) = \text{Pos } A \wedge \text{count } C (\text{Pos } A) \leq 1 \wedge \neg$

interp $C \models_h C \wedge S C = \{\#\}\}$

unfolding *interp-def* **by** (*rule production.simps*)

abbreviation *productive* $A \equiv (\text{production } A \neq \{\})$

abbreviation *produces* :: 'a clause \Rightarrow 'a \Rightarrow bool **where**

produces $C A \equiv \text{production } C = \{A\}$

lemma *producesD*:

produces $C A \implies C \in N \wedge C \neq \{\#\} \wedge \text{Pos } A = \text{Max}(\text{set-mset } C) \wedge \text{count } C (\text{Pos } A) \leq 1 \wedge \neg$

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 $C = (\bigcup D \in \{D \in N. D \# \subset \# C\}. \text{production } D)$

unfolding *interp-def* **apply** *auto*

unfolding *production-unfold* **apply** *auto*

done

lemma *production-iff-produces*:

produces $D A \longleftrightarrow A \in \text{production } D$

unfolding *production-unfold* **by** *auto*

definition *Interp* :: 'a clause \Rightarrow 'a interp **where**

Interp $C = \text{interp } C \cup \text{production } C$

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**

$INTERP = (\bigcup D \in N. \text{ production } D)$

lemma *interp-subseteq-Interp[simp]*: $\text{interp } C \subseteq \text{Interp } C$
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*: $A \notin \text{Interp } C \implies A \in \text{interp } D \implies C \# \subset \# D$
using *less-eq-imp-interp-subseteq-Interp multiset-linorder.not-less* **by** *blast*

lemma *false-interp-to-true-interp-imp-less-multiset*: $A \notin \text{interp } C \implies A \in \text{interp } D \implies C \# \subset \# D$
using *less-eq-imp-interp-subseteq-interp multiset-linorder.not-less* **by** *blast*

lemma *false-Interp-to-true-Interp-imp-less-multiset*: $A \notin \text{Interp } C \implies A \in \text{Interp } D \implies C \# \subset \# D$
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 $D \# \subset \# \{\# \text{Neg } A \# \}$
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[unfolded 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': $D \# \subset \# D'$ **and**

c-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-in-c*: $\text{Pos } A \in \# C$ **and** *a-at-d*: $A \in \text{Interp } D$

by *blast*

from *a-at-d* **have** $A \in \text{interp } D'$

using *d-lt-d'* *less-imp-Interp-subseteq-interp* **by** *blast*

thus *?thesis*

using *subs a-in-c* **by** (*blast dest: contra-subsetD*)

next

case *False*

then obtain *A* **where** *a-in-c*: $\text{Neg } A \in \# C$ **and** $A \notin \text{Interp } D$

using *c-at-d* *unfolding true-cls-def* **by** *blast*

hence $\bigwedge D''. \neg \text{produces } D'' A$

using *c-le-d* *neg-notin-Interp-not-produce* **by** *simp*

thus *?thesis*

using *a-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*

true-Interp-imp-general[*OF* - *less-multiset-right-total*]

by *simp*

lemma *true-interp-imp-general*:

assumes

c-le-d: $C \# \subseteq \# D$ **and**

d-lt-d': $D \# \subset \# D'$ **and**

c-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-in-c*: $\text{Pos } A \in \# C$ **and** *a-at-d*: $A \in \text{interp } D$

by *blast*

from *a-at-d* **have** $A \in \text{interp } D'$

using *d-lt-d'* *less-eq-imp-interp-subseteq-interp*[*OF multiset-order.less-imp-le*] **by** *blast*

thus *?thesis*

using *subs a-in-c* **by** (*blast dest: contra-subsetD*)

next

case *False*

then obtain *A* **where** *a-in-c*: $\text{Neg } A \in \# C$ **and** $A \notin \text{interp } D$

using *c-at-d* *unfolding true-cls-def* **by** *blast*

hence $\bigwedge D''. \neg \text{produces } D'' A$
 using *c-le-d* by (auto dest: produces-imp-in-interp less-eq-imp-interp-subseteq-interp)
 thus ?thesis
 using *a-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) *count* $C (Pos P) \geq 2$
 | (Q) Q where $Q > Pos P$ 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 ∈# D
| (Q) Q where Q > Neg P and count D Q > 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 ∈ set-mset D
  using Q(2) by (auto split: split-if-asm)
then have Max (set-mset D) > Neg P
  using Q(1) Max-gr-iff by blast
hence Max (set-mset D) > 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 Max (set-mset D) > 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 ∈ INTERP
shows ∃ D. D + {#Pos P#} ∈ N ∧ produces (D + {#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 $MMax\ M \equiv Max\ (set-mset\ M)$

21.6 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* $(C + \{\#Pos\ P\# \} + \{\#Pos\ P\# \})\ B\ (C + \{\#Pos\ P\# \})\ |$
superposition-l: *superposition-rules* $(C_1 + \{\#Pos\ P\# \})\ (C_2 + \{\#Neg\ P\# \})\ (C_1 + C_2)$

inductive *superposition* :: 'a clauses \Rightarrow 'a clauses \Rightarrow bool **where**
superposition: $A \in N \Longrightarrow B \in N \Longrightarrow superposition\ rules\ A\ B\ C$
 $\Longrightarrow superposition\ N\ (N \cup \{C\})$

definition *abstract-red* :: 'a::wellorder clause \Rightarrow 'a clauses \Rightarrow bool **where**
abstract-red $C\ N = (class-lt\ N\ C \models_p C)$

lemma *less-multiset[iff]*: $M < N \iff M \# \subset \# N$
unfolding *less-multiset-def* **by** auto

lemma *less-eq-multiset[iff]*: $M \leq N \iff M \# \subseteq \# N$
unfolding *less-eq-multiset-def* **by** auto

lemma *herbrand-true-clss-true-clss-clss-herbrand-true-clss*:
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 | 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 | a. a  $\in$  atms-of B  $\wedge$  a  $\notin$  atms-of-s I}))  $\in$  I
     $\cup$  {Pos a | a. a  $\in$  atms-of B  $\wedge$  a  $\notin$  atms-of-s I}
     $\vee$  Neg (aa (atms-of-ms A  $\cup$  atms-of-ms {B})
      (I  $\cup$  {Pos a | a. a  $\in$  atms-of B  $\wedge$  a  $\notin$  atms-of-s I}))  $\in$  I
       $\cup$  {Pos a | a. a  $\in$  atms-of B  $\wedge$  a  $\notin$  atms-of-s I}
    )
by auto
hence total-over-set (I  $\cup$  {Pos a | a. a  $\in$  atms-of B  $\wedge$  a  $\notin$  atms-of-s I}) (atms-of-ms A  $\cup$  atms-of-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-cls-def by auto
thus ?thesis
oops
lemma
assumes
  CP:  $\neg$  clss-lt N ({#C#} + {#E#})  $\models_p$  {#C#} + {#Neg P#} and
  clss-lt N ({#C#} + {#E#})  $\models_p$  {#E#} + {#Pos P#}  $\vee$  clss-lt N ({#C#} + {#E#})  $\models_p$ 
{#C#} + {#Neg P#}
shows clss-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: redundant A N  $\longleftrightarrow$  abstract-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  $\longrightarrow$   $\neg$ redundant A N  $\longrightarrow$   $\neg$ redundant B N
       $\longrightarrow$  superposition-rules A B C  $\longrightarrow$  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.  $\neg$ ?NI  $\models_h$  E}  $\neq$  {}
  unfolding true-clss-def Ball-def by auto
def D  $\equiv$  Min {E $\in$ N.  $\neg$ ?NI  $\models_h$  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:  $\neg$ ?NI  $\models_h$  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:  $\bigwedge E. E \in N \implies E \neq D \implies \neg ?N_{\mathcal{I}} \models_h E \implies D \leq E$ 
  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-clss-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:  $\text{count } D L = 1$ 
  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

```


$\text{true-interp-imp-INTERP}$ **unfolding** $\text{production-iff-produces}$ **unfolding** production-unfold
 by (auto simp add: max not-empty)
 hence $\text{INTERP } N \models_h D$
 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 $L = \text{this}(1)$
 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
 $\text{DPN}: E + \{\#Pos P\# \} \in N$ and
 $\text{prod}: \text{production } N (E + \{\#Pos P\# \}) = \{P\}$
 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
 $\text{PMax}: \text{Pos } P = \text{MMax } (E + \{\#Pos P\# \})$ and
 $\text{count } (E + \{\#Pos P\# \}) (\text{Pos } P) \leq 1$ and
 $S (E + \{\#Pos P\# \}) = \{\# \}$ and
 $\neg \text{interp } N (E + \{\#Pos P\# \}) \models_h E + \{\#Pos P\# \}$
 using prod unfolding production-unfold by auto
 have $\text{Neg } P \notin \# E$
 using prod produces-imp-neg-notin-lits by force
 hence $\bigwedge y. y \in \# (E + \{\#Pos P\# \})$
 $\implies \text{count } (E + \{\#Pos P\# \}) (\text{Neg } P) < \text{count } (C + \{\#Neg P\# \}) (\text{Neg } P)$

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-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 red'[simplified]: $\neg ?thesis$
 have abs: $\text{clss-lt } N (C + E) \models_p C + E$
 using redundant-iff-abstract red' unfolding abstract-red-def by auto
 have $\text{clss-lt } N (C + E) \models_p E + \{\#Pos P\} \vee \text{clss-lt } N (C + E) \models_p C + \{\#Neg P\}$
 proof clarify
 assume CP: $\neg \text{clss-lt } N (C + E) \models_p C + \{\#Neg P\}$
 { fix I
 assume
 total-over-m I $(\text{clss-lt } N (C + E) \cup \{E + \{\#Pos P\}\})$ and
 consistent-interp I and
 I $\models_s \text{clss-lt } N (C + E)$
 hence I $\models C + E$
 using abs sorry
 moreover have $\neg I \models C + \{\#Neg P\}$
 using CP unfolding true-clss-cls-def
 sorry
 ultimately have I $\models E + \{\#Pos P\}$ by auto
 }
 then show $\text{clss-lt } N (C + E) \models_p E + \{\#Pos P\}$
 unfolding true-clss-cls-def by auto
 qed
 moreover have $\text{clss-lt } N (C + E) \subseteq \text{clss-lt } N (C + \{\#Neg P\})$
 using ce-lt-d mult-less-trans unfolding clss-lt-def D L by force
 ultimately have $\text{redundant } (C + \{\#Neg P\}) N \vee \text{clss-lt } N (C + E) \models_p E + \{\#Pos P\}$
 unfolding redundant-iff-abstract abstract-red-def using true-clss-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:  $\neg INTERP\ N \models_h C + E$ 
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-cl-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-cl-def Partial-Clausal-Logic.true-clss-def
  by blast
qed

```

```

inductive redundant :: 'a clause  $\Rightarrow$  'a clauses  $\Rightarrow$  bool where
  subsumption:  $A \in N \Longrightarrow A \subset\# B \Longrightarrow$  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

```

22 Implementation for 2 Watched-Literals

```

theory CDCL-Two-Watched-Literals-Implementation
imports CDCL-Two-Watched-Literals DPLL-CDCL-W-Implementation
begin

type-synonym conc-tw-l-state =
  ((nat, nat, nat literal list) marked-lit, nat literal list twl-clause list, nat, nat literal list)
  twl-state

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

abbreviation convert-tr :: ('a, 'b, 'c list) marked-lits  $\Rightarrow$  ('a, 'b, 'c multiset) marked-lits
  where
  convert-tr  $\equiv$  map convert

abbreviation convertC :: 'a literal list option  $\Rightarrow$  'a clause option where
  convertC  $\equiv$  map-option mset

fun raw-clause-l :: 'v list twl-clause  $\Rightarrow$  'v multiset twl-clause where
  raw-clause-l (TWL-Clause UW W) = TWL-Clause (mset W) (mset UW)

abbreviation convert-clss :: 'v literal list twl-clause list  $\Rightarrow$  'v clause twl-clause multiset
  where
  convert-clss S  $\equiv$  mset (map raw-clause-l S)

fun raw-state-of-conc :: conc-tw-l-state  $\Rightarrow$  (nat, nat, nat clause) twl-state-abs where
  raw-state-of-conc (TWL-State M N U k C) =
    TWL-State (convert-tr M) (convert-clss N) (convert-clss U) k (map-option mset C)

lemma
  raw-state-of-conc (tl-trail S) = tl-trail (raw-state-of-conc S)
  unfolding tl-trail-def by (induction S) (auto simp: map-tl)

definition watch-nat :: conc-tw-l-state  $\Rightarrow$  nat literal list  $\Rightarrow$  nat literal list twl-clause where

```

```

watch-nat S C =
  (let
    C' = remdups C;
    negation-not-assigned = filter (λL. ¬L ∈ lits-of (trail S)) C';
    negation-assigned-sorted-by-trail = filter (λL. L ∈ set C) (map (λL. ¬lit-of L) (trail S));
    W = take 2 (negation-not-assigned @ negation-assigned-sorted-by-trail);
    UW = foldl (λa l. remove1 l a) C W
  in TWL-Clause W UW)

```

definition

```

rewatch-nat ::
  (nat, nat, nat literal list) marked-lit ⇒ conc-twl-state ⇒
  nat literal list twl-clause ⇒ nat literal list twl-clause

```

where

```

rewatch-nat L S C =
  (if ¬ lit-of L ∈ set (watched C) then
    case filter (λL'. L' ∉ set (watched C) ∧ ¬ L' ∈ lits-of (L # trail S))
      (unwatched C) of
      [] ⇒ C
    | L' # - ⇒
      TWL-Clause (L' # remove1 (¬ lit-of L) (watched C))
        (¬ lit-of L # remove1 L' (unwatched C))
  else
    C)

```

definition raw-candidates-conflict :: conc-twl-state ⇒ nat literal list list **where**

```

raw-candidates-conflict S =
  map (λT. case T of TWL-Clause W UW ⇒ W @ UW)
    (filter (λC. set (watched C) ⊆ (uminus ' lits-of (trail S)))
      (init-clss S @ learned-clss S))

```

definition do-conflict-step :: conc-twl-state ⇒ conc-twl-state option **where**

```

do-conflict-step S =
  (case conflicting S of
    Some - ⇒ None
  | None ⇒
    (case raw-candidates-conflict S of
      [] ⇒ None
    | a # - ⇒ Some (update-conflicting (Some a) S)))

```

end