

Formalisation of Ground Resolution and CDCL in Isabelle/HOL

Mathias Fleury and Jasmin Blanchette

June 21, 2016

Contents

1	More Standard Theorems	7
1.1	More about Multisets	7
1.1.1	Basic Setup	7
1.1.2	Lemmas about intersections	7
1.1.3	Lemmas about size	8
1.1.4	Multiset Extension of Multiset Ordering	9
1.1.5	Remove	10
1.1.6	Replicate	11
1.1.7	Multiset and set conversion	11
1.1.8	Removing duplicates	12
1.1.9	Filter	16
1.1.10	Sums	17
1.1.11	Order	17
1.2	Transitions	17
1.2.1	More theorems about Closures	18
1.2.2	Full Transitions	19
1.2.3	Well-Foundedness and Full Transitions	20
1.2.4	More Well-Foundedness	21
1.3	Various Lemmas	23
1.4	More List	25
1.4.1	<i>upt</i>	25
1.4.2	Lexicographic Ordering	28
1.4.3	Remove	28
2	Definition of Entailment	31
2.1	Clausal Logic	31
2.1.1	Literals	31
2.1.2	Clauses	34
2.2	Herbrand Intepretation	36
2.2.1	Herbrand Interpretations	36
2.3	Partial Clausal Logic	38
2.3.1	Clauses	38
2.3.2	Partial Interpretations	38
2.3.3	Subsumptions	54
2.3.4	Removing Duplicates	55
2.3.5	Set of all Simple Clauses	55
2.3.6	Experiment: Expressing the Entailments as Locales	59
2.3.7	Entailment to be extended	59

3	Normalisation	63
3.1	Logics	63
3.1.1	Definition and abstraction	63
3.1.2	properties of the abstraction	64
3.1.3	Subformulas and properties	67
3.1.4	Positions	70
3.2	Semantics over the syntax	73
3.3	Rewrite systems and properties	74
3.3.1	Lifting of rewrite rules	74
3.3.2	Consistency preservation	77
3.3.3	Full Lifting	78
3.4	Transformation testing	78
3.4.1	Definition and first properties	78
3.4.2	Invariant conservation	81
3.5	Rewrite Rules	84
3.5.1	Elimination of the equivalences	84
3.5.2	Eliminate Implication	86
3.5.3	Eliminate all the True and False in the formula	87
3.5.4	PushNeg	93
3.5.5	Push inside	98
3.6	The full transformations	112
3.6.1	Abstract Property characterizing that only some connective are inside the others	112
3.6.2	Conjunctive Normal Form	114
3.6.3	Disjunctive Normal Form	115
3.7	More aggressive simplifications: Removing true and false at the beginning	116
3.7.1	Transformation	116
3.7.2	More invariants	118
3.7.3	The new CNF and DNF transformation	122
3.8	Link with Multiset Version	123
3.8.1	Transformation to Multiset	123
3.8.2	Equisatisfiability of the two Version	123
4	Resolution-based techniques	127
4.1	Resolution	127
4.1.1	Simplification Rules	127
4.1.2	Unconstrained Resolution	129
4.1.3	Inference Rule	129
4.1.4	Lemma about the simplified state	144
4.1.5	Resolution and Invariants	147
4.2	Superposition	167
4.2.1	We can now define the rules of the calculus	174
4.3	Partial Clausal Logic	180
4.3.1	Decided Literals	180
4.3.2	Backtracking	184
4.3.3	Decomposition with respect to the First Decided Literals	185
4.3.4	Negation of Clauses	192
4.3.5	Other	196
4.3.6	Extending Entailments to multisets	197

5	NOT's CDCL and DPLL	199
5.1	Measure	199
5.2	NOT's CDCL	203
5.2.1	Auxiliary Lemmas and Measure	203
5.2.2	Initial definitions	204
5.2.3	DPLL with backjumping	208
5.2.4	CDCL	224
5.2.5	CDCL with restarts	246
5.2.6	Merging backjump and learning	254
5.2.7	Instantiations	265
5.3	DPLL as an instance of NOT	280
5.3.1	DPLL with simple backtrack	280
5.3.2	Adding restarts	285
5.4	Weidenbach's DPLL	285
5.4.1	Rules	285
5.4.2	Invariants	286
5.4.3	Termination	294
5.4.4	Final States	296
5.4.5	Link with NOT's DPLL	298
6	Weidenbach's CDCL	305
6.1	Weidenbach's CDCL with Multisets	305
6.1.1	The State	305
6.1.2	CDCL Rules	313
6.1.3	Structural Invariants	319
6.1.4	CDCL Strong Completeness	346
6.1.5	Higher level strategy	347
6.1.6	Termination	391
6.2	Merging backjump rules	413
6.2.1	Inclusion of the states	413
6.2.2	More lemmas conflict-propagate and backjumping	415
6.2.3	CDCL with Merging	430
6.2.4	CDCL with Merge and Strategy	435
6.3	Link between Weidenbach's and NOT's CDCL	469
6.3.1	Inclusion of the states	469
6.3.2	Additional Lemmas between NOT and W states	472
6.3.3	Inclusion of Weidenbach's CDCL in NOT's CDCL	474
6.3.4	Correctness of <i>cdcl_W-merge-stgy</i>	479
6.3.5	Adding Restarts	481
6.4	Incremental SAT solving	491
7	Implementation of DPLL and CDCL	503
7.1	Simple List-Based Implementation of the DPLL and CDCL	503
7.1.1	Common Rules	503
7.1.2	CDCL specific functions	506
7.1.3	Simple Implementation of DPLL	508
7.1.4	List-based CDCL Implementation	518
7.1.5	CDCL Implementation	521
7.1.6	Abstract Clause Representation	547
7.2	Weidenbach's CDCL with Abstract Clause Representation	548

7.2.1	Instantiation of the Multiset Version	548
7.2.2	Abstract Relation and Relation Theorems	550
7.2.3	The State	555
7.2.4	CDCL Rules	563
7.2.5	Higher level strategy	578
7.3	2-Watched-Literal	582
7.3.1	Essence of 2-WL	583
7.3.2	Two Watched-Literals with invariant	604

Chapter 1

More Standard Theorems

This chapter contains additional lemmas built on top of HOL.

end

```
theory Multiset-More
imports ~~/src/HOL/Library/Multiset-Order
begin
```

1.1 More about Multisets

Isabelle's theory of finite multisets is not as developed as other areas, such as lists and sets. The present theory introduces some missing concepts and lemmas. Some of it is expected to move to Isabelle's library.

1.1.1 Basic Setup

declare

diff-single-trivial [simp]

in-image-mset [iff]

image-mset.compositionality [simp]

mset-leD[*dest*, *intro?*]

Multiset.in-multiset-in-set[simp]

lemma *image-mset-cong2*[*cong*]:

$(\bigwedge x. x \in \# M \implies f x = g x) \implies M = N \implies \text{image-mset } f M = \text{image-mset } g N$

by (*hypsubst*, *rule image-mset-cong*)

lemma *subset-msetE* [*elim!*]:

$[| A \subset \# B; | A \subseteq \# B; \sim (B \subseteq \# A) |] \implies R \implies R$

unfolding *subteq-mset-def subset-mset-def* **by** (*meson mset-less-eqI subset-mset.eq-iff*)

1.1.2 Lemmas about intersections

lemma *mset-inter-single*:

$x \in \# \Sigma \implies \Sigma \# \cap \{\#x\# \} = \{\#x\# \}$
 $x \notin \# \Sigma \implies \Sigma \# \cap \{\#x\# \} = \{\# \}$
apply (*simp add: mset-le-single subset-mset.inf-absorb2*)
by (*simp add: multiset-inter-def*)

1.1.3 Lemmas about size

This sections adds various lemmas about size. Most lemmas have a finite set equivalent.

lemma *size-mset-SucE*: $\text{size } A = \text{Suc } n \implies (\bigwedge a B. A = \{\#a\# \} + B \implies \text{size } B = n \implies P) \implies P$
by (*cases A*) (*auto simp add: ac-simps*)

lemma *size-Suc-Diff1*:
 $x \in \# \Sigma \implies \text{Suc } (\text{size } (\Sigma - \{\#x\# \})) = \text{size } \Sigma$
using *arg-cong[OF insert-DiffM, of - - size]* **by** *simp*

lemma *size-Diff-singleton*: $x \in \# \Sigma \implies \text{size } (\Sigma - \{\#x\# \}) = \text{size } \Sigma - 1$
by (*simp add: size-Suc-Diff1 [symmetric]*)

lemma *size-Diff-singleton-if*: $\text{size } (A - \{\#x\# \}) = (\text{if } x \in \# A \text{ then } \text{size } A - 1 \text{ else } \text{size } A)$
by (*simp add: size-Diff-singleton*)

lemma *size-Un-Int*:
 $\text{size } A + \text{size } B = \text{size } (A \# \cup B) + \text{size } (A \# \cap B)$
proof –
have *: $A + B = B + (A - B + (A - (A - B)))$
by (*simp add: subset-mset.add-diff-inverse union-commute*)
have $\text{size } B + \text{size } (A - B) = \text{size } A + \text{size } (B - A)$
unfolding *size-union[symmetric] subset-mset.sup-commute sup-subset-mset-def[symmetric]*
by *blast*
then show *?thesis* **unfolding** *multiset-inter-def size-union[symmetric]* *
by (*auto simp add: sup-subset-mset-def*)
qed

lemma *size-Un-disjoint*:
assumes $A \# \cap B = \{\# \}$
shows $\text{size } (A \# \cup B) = \text{size } A + \text{size } B$
using *assms size-Un-Int [of A B]* **by** *simp*

lemma *size-Diff-subset-Int*:
shows $\text{size } (\Sigma - \Sigma') = \text{size } \Sigma - \text{size } (\Sigma \# \cap \Sigma')$
proof –
have *: $\Sigma - \Sigma' = \Sigma - \Sigma \# \cap \Sigma'$ **by** (*auto simp add: multiset-eq-iff*)
show *?thesis* **unfolding** * **using** *size-Diff-submset subset-mset.inf.cobounded1* **by** *blast*
qed

lemma *diff-size-le-size-Diff*: $\text{size } (\Sigma :: \text{multiset}) - \text{size } \Sigma' \leq \text{size } (\Sigma - \Sigma')$
proof –
have $\text{size } \Sigma - \text{size } \Sigma' \leq \text{size } \Sigma - \text{size } (\Sigma \# \cap \Sigma')$
using *size-mset-mono diff-le-mono2 subset-mset.inf-le2* **by** *blast*
also have $\dots = \text{size } (\Sigma - \Sigma')$ **by** (*simp add: size-Diff-subset-Int*)
finally show *?thesis* .
qed

lemma *size-Diff1-less*: $x \in \# \Sigma \implies \text{size } (\Sigma - \{\#x\# \}) < \text{size } \Sigma$
apply (*rule Suc-less-SucD*)

by (simp add: size-Suc-Diff1)

lemma size-Diff2-less: $x \in \# \Sigma \implies y \in \# \Sigma \implies \text{size } (\Sigma - \{\#x\} - \{\#y\}) < \text{size } \Sigma$
 using nonempty-has-size by (fastforce intro!: diff-Suc-less simp add: size-Diff1-less
 size-Diff-subset-Int mset-inter-single)

lemma size-Diff1-le: $\text{size } (\Sigma - \{\#x\}) \leq \text{size } \Sigma$
 by (cases $x \in \# \Sigma$) (simp-all add: size-Diff1-less less-imp-le)

lemma size-psubset: $(\Sigma :: \text{multiset}) \leq \# \Sigma' \implies \text{size } \Sigma < \text{size } \Sigma' \implies \Sigma < \# \Sigma'$
 using less-irrefl subset-mset-def by blast

1.1.4 Multiset Extension of Multiset Ordering

The $op \# \subset \# \#$ and $op \# \subseteq \# \#$ operators are introduced as the multiset extension of the multiset orderings of $op \# \subset \#$ and $op \# \subseteq \#$.

definition less-mset-mset :: $('a :: \text{order}) \text{ multiset multiset} \Rightarrow 'a \text{ multiset multiset} \Rightarrow \text{bool}$
 (infix $\# < \# \#$ 50)

where

$M' \# < \# \# M \longleftrightarrow (M', M) \in \text{mult } \{(x', x). x' \# < \# x\}$

definition le-mset-mset :: $('a :: \text{order}) \text{ multiset multiset} \Rightarrow 'a \text{ multiset multiset} \Rightarrow \text{bool}$
 (infix $\# \leq \# \#$ 50)

where

$M' \# \leq \# \# M \longleftrightarrow M' \# < \# \# M \vee M' = M$

notation less-mset-mset (infix $\# \subset \# \#$ 50)

notation le-mset-mset (infix $\# \subseteq \# \#$ 50)

lemmas less-mset-mset_{DM} = order.mult_{DM}[OF order-multiset, folded less-mset-mset-def]

lemmas less-mset-mset_{HO} = order.mult_{HO}[OF order-multiset, folded less-mset-mset-def]

interpretation multiset-multiset-order: order

le-mset-mset :: $('a :: \text{linorder}) \text{ multiset multiset} \Rightarrow ('a :: \text{linorder}) \text{ multiset multiset} \Rightarrow \text{bool}$

less-mset-mset :: $('a :: \text{linorder}) \text{ multiset multiset} \Rightarrow ('a :: \text{linorder}) \text{ multiset multiset} \Rightarrow \text{bool}$

unfolding less-mset-mset-def[abs-def] le-mset-mset-def[abs-def] less-multiset-def[abs-def]

by (rule order.order-mult)+ standard

interpretation multiset-multiset-linorder: linorder

le-mset-mset :: $('a :: \text{linorder}) \text{ multiset multiset} \Rightarrow ('a :: \text{linorder}) \text{ multiset multiset} \Rightarrow \text{bool}$

less-mset-mset :: $('a :: \text{linorder}) \text{ multiset multiset} \Rightarrow ('a :: \text{linorder}) \text{ multiset multiset} \Rightarrow \text{bool}$

unfolding less-mset-mset-def[abs-def] le-mset-mset-def[abs-def]

by (rule linorder.linorder-mult[OF linorder-multiset])

lemma wf-less-mset-mset: wf $\{(\Sigma :: ('a :: \text{wellorder}) \text{ multiset multiset}, T). \Sigma \# \subset \# \# T\}$

unfolding less-mset-mset-def by (auto intro: wf-mult wf-less-multiset)

interpretation multiset-multiset-wellorder: wellorder

le-mset-mset :: $('a :: \text{wellorder}) \text{ multiset multiset} \Rightarrow ('a :: \text{wellorder}) \text{ multiset multiset} \Rightarrow \text{bool}$

less-mset-mset :: $('a :: \text{wellorder}) \text{ multiset multiset} \Rightarrow ('a :: \text{wellorder}) \text{ multiset multiset} \Rightarrow \text{bool}$

by unfold-locales (blast intro: wf-less-mset-mset[unfolded wf-def, rule-format])

lemma union-less-mset-mset-mono2: $B \# \subset \# \# D \implies C + B \# \subset \# \# C + (D :: 'a :: \text{order multiset multiset})$

apply (unfold less-mset-mset-def mult-def)

apply (erule trancl-induct)
apply (blast intro: mult1-union)
apply (blast intro: mult1-union trancl-trans)
done

lemma union-less-mset-mset-diff-plus:
 $U \leq \# \Sigma \implies T \# \subset \# \# U \implies \Sigma - U + T \# \subset \# \# \Sigma$
apply (erule subset-mset.diff-add[symmetric])
using union-less-mset-mset-mono2[of $T U \Sigma - U$] **by** simp

lemma ex-gt-imp-less-mset-mset:
 $(\exists y :: 'a :: \text{linorder multiset} \in \# T. (\forall x. x \in \# \Sigma \longrightarrow x \# \subset \# y)) \implies \Sigma \# \subset \# \# T$
using less-mset-mset_{HO} **by** (metis count-greater-zero-iff count-inI less-nat-zero-code
 multiset-linorder.not-less-iff-gr-or-eq)

1.1.5 Remove

lemma set-mset-minus-replicate-mset[simp]:
 $n \geq \text{count } A \ a \implies \text{set-mset } (A - \text{replicate-mset } n \ a) = \text{set-mset } A - \{a\}$
 $n < \text{count } A \ a \implies \text{set-mset } (A - \text{replicate-mset } n \ a) = \text{set-mset } A$
unfolding set-mset-def **by** (auto split: if-split simp: not-in-iff)

abbreviation removeAll-mset :: $'a \Rightarrow 'a \text{ multiset} \Rightarrow 'a \text{ multiset}$ **where**
 removeAll-mset $C \ M \equiv M - \text{replicate-mset } (\text{count } M \ C) \ C$

lemma mset-removeAll[simp, code]:
 removeAll-mset $C \ (\text{mset } L) = \text{mset } (\text{removeAll } C \ L)$
by (induction L) (auto simp: ac-simps multiset-eq-iff split: if-split-asm)

lemma removeAll-mset-filter-mset:
 removeAll-mset $C \ M = \text{filter-mset } (op \neq C) \ M$
by (induction M) (auto simp: ac-simps multiset-eq-iff)

abbreviation remove1-mset :: $'a \Rightarrow 'a \text{ multiset} \Rightarrow 'a \text{ multiset}$ **where**
 remove1-mset $C \ M \equiv M - \{\#C\# \}$

lemma remove1-mset-remove1[code]:
 remove1-mset $C \ (\text{mset } L) = \text{mset } (\text{remove1 } C \ L)$
by auto

lemma in-remove1-mset-neg:
assumes $ab: a \neq b$
shows $a \in \# \text{remove1-mset } b \ C \longleftrightarrow a \in \# C$

proof –

have $\text{count } \{\#b\# \} \ a = 0$
using ab **by** simp
then show ?thesis
by (metis (no-types) count-diff diff-zero mem-Collect-eq set-mset-def)

qed

lemma size-mset-removeAll-mset-le-iff:
 $\text{size } (\text{removeAll-mset } x \ M) < \text{size } M \longleftrightarrow x \in \# M$
apply (rule iffI)
apply (force intro: count-inI)
apply (rule mset-less-size)
apply (auto simp: subset-mset-def multiset-eq-iff)

done

lemma *size-mset-remove1-mset-le-iff*:
 $\text{size } (\text{remove1-mset } x \ M) < \text{size } M \longleftrightarrow x \in \# \ M$
apply (rule *iffI*)
using *less-irrefl* **apply** *fastforce*
apply (rule *mset-less-size*)
by (auto elim: *in-countE simp: subset-mset-def multiset-eq-iff*)

lemma *set-mset-remove1-mset[simp]*:
 $\text{set-mset } (\text{remove1-mset } L \ (\text{mset } W)) = \text{set } (\text{remove1 } L \ W)$
by (*metis mset-remove1 set-mset-mset*)

1.1.6 Replicate

lemma *replicate-mset-plus*: $\text{replicate-mset } (a + b) \ C = \text{replicate-mset } a \ C + \text{replicate-mset } b \ C$
by (*induct a*) (auto *simp: ac-simps*)

lemma *mset-replicate-replicate-mset*:
 $\text{mset } (\text{replicate } n \ L) = \text{replicate-mset } n \ L$
by (*induction n*) *auto*

lemma *set-mset-single-iff-replicate-mset*:
 $\text{set-mset } U = \{a\} \longleftrightarrow (\exists n > 0. U = \text{replicate-mset } n \ a) \text{ (is } ?S \longleftrightarrow ?R)$

proof

assume *?R*

then show *?S* **by** *auto*

next

assume *?S*

show *?R*

proof (rule *ccontr*)

assume $\neg ?R$

have $\forall n. U \neq \text{replicate-mset } n \ a$

using $\langle ?S \rangle \langle \neg ?R \rangle$ **by** (*metis gr-zeroI insert-not-empty set-mset-replicate-mset-subset*)

then obtain *b* **where** $b \in \# \ U$ **and** $b \neq a$

by (*metis count-replicate-mset mem-Collect-eq multiset-eqI neq0-conv set-mset-def*)

then show *False*

using $\langle ?S \rangle$ **by** *auto*

qed

qed

1.1.7 Multiset and set conversion

lemma *count-mset-set-if*:
 $\text{count } (\text{mset-set } A) \ a = (\text{if } a \in A \wedge \text{finite } A \text{ then } 1 \text{ else } 0)$
by *auto*

lemma *mset-set-set-mset-empty-mempty[iff]*:
 $\text{mset-set } (\text{set-mset } D) = \{\#\} \longleftrightarrow D = \{\#\}$
by (auto *dest: arg-cong[of - - set-mset]*)

lemma *size-mset-set-card*:
 $\text{finite } S \implies \text{size } (\text{mset-set } S) = \text{card } S$
by (*induction S* rule: *finite-induct*) *auto*

lemma *count-mset-set-le-one*: $\text{count } (\text{mset-set } A) \ x \leq 1$

by (metis count-mset-set(1) count-mset-set(2) count-mset-set(3) eq-iff le-numeral-extra(1))

lemma mset-set-subseteq-mset-set[iff]:

assumes finite A finite B

shows mset-set A $\subseteq\#$ mset-set B \longleftrightarrow A \subseteq B

by (metis assms contra-subsetD count-mset-set(1,3) count-mset-set-le-one finite-set-mset-mset-set less-eq-nat.simps(1) mset-less-eqI set-mset-mono)

lemma mset-set-set-mset-subseteq[simp]: mset-set (set-mset A) $\subseteq\#$ A

by (metis count-mset-set(1,3) finite-set-mset less-eq-nat.simps(1) less-one mem-Collect-eq mset-less-eqI not-less set-mset-def)

lemma mset-sorted-list-of-set[simp]:

mset (sorted-list-of-set A) = mset-set A

by (metis mset-sorted-list-of-multiset sorted-list-of-mset-set)

lemma mset-take-subseteq: mset (take n xs) $\subseteq\#$ mset xs

apply (induct xs arbitrary: n)

apply simp

by (case-tac n) simp-all

1.1.8 Removing duplicates

definition remdups-mset :: 'v multiset \Rightarrow 'v multiset **where**

remdups-mset S = mset-set (set-mset S)

lemma remdups-mset-in[iff]: a $\in\#$ remdups-mset A \longleftrightarrow a $\in\#$ A

unfolding remdups-mset-def by auto

lemma count-remdups-mset-eq-1: a $\in\#$ remdups-mset A \longleftrightarrow count (remdups-mset A) a = 1

unfolding remdups-mset-def by (auto simp: count-eq-zero-iff intro: count-inI)

lemma remdups-mset-empty[simp]:

remdups-mset {#} = {#}

unfolding remdups-mset-def by auto

lemma remdups-mset-singleton[simp]:

remdups-mset {#a#} = {#a#}

unfolding remdups-mset-def by auto

lemma set-mset-remdups[simp]: set-mset (remdups-mset C) = set-mset C

by auto

lemma remdups-mset-eq-empty[iff]:

remdups-mset D = {#} \longleftrightarrow D = {#}

unfolding remdups-mset-def by blast

lemma remdups-mset-singleton-sum[simp]:

remdups-mset ({#a#} + A) = (if a $\in\#$ A then remdups-mset A else {#a#} + remdups-mset A)

remdups-mset (A + {#a#}) = (if a $\in\#$ A then remdups-mset A else {#a#} + remdups-mset A)

unfolding remdups-mset-def by (simp-all add: insert-absorb)

lemma mset-remdups-remdups-mset[simp]:

mset (remdups D) = remdups-mset (mset D)

by (induction D) (auto simp add: ac-simps)

definition *distinct-mset* :: 'a multiset \Rightarrow bool **where**
distinct-mset $S \longleftrightarrow (\forall a. a \in \# S \longrightarrow \text{count } S \ a = 1)$

lemma *distinct-mset-empty[simp]*: *distinct-mset* $\{\#\}$
unfolding *distinct-mset-def* **by** *auto*

lemma *distinct-mset-singleton[simp]*: *distinct-mset* $\{\#a\#\}$
unfolding *distinct-mset-def* **by** *auto*

definition *distinct-mset-set* :: 'a multiset set \Rightarrow bool **where**
distinct-mset-set $\Sigma \longleftrightarrow (\forall S \in \Sigma. \text{distinct-mset } S)$

lemma *distinct-mset-set-empty[simp]*:
distinct-mset-set $\{\}$
unfolding *distinct-mset-set-def* **by** *auto*

lemma *distinct-mset-set-singleton[iff]*:
distinct-mset-set $\{A\} \longleftrightarrow \text{distinct-mset } A$
unfolding *distinct-mset-set-def* **by** *auto*

lemma *distinct-mset-set-insert[iff]*:
distinct-mset-set (*insert* $S \ \Sigma$) $\longleftrightarrow (\text{distinct-mset } S \wedge \text{distinct-mset-set } \Sigma)$
unfolding *distinct-mset-set-def* **by** *auto*

lemma *distinct-mset-set-union[iff]*:
distinct-mset-set ($\Sigma \cup \Sigma'$) $\longleftrightarrow (\text{distinct-mset-set } \Sigma \wedge \text{distinct-mset-set } \Sigma')$
unfolding *distinct-mset-set-def* **by** *auto*

lemma *distinct-mset-union*:
assumes *dist*: *distinct-mset* ($A + B$)
shows *distinct-mset* A

proof –

obtain *aa* :: 'a multiset \Rightarrow 'a **where**
f2: $\forall m. \neg \text{distinct-mset } m \vee (\forall a. (a::'a) \notin \# m \vee \text{count } m \ a = 1)$
 $\forall m. aa \ m \in \# m \wedge \text{count } m \ (aa \ m) \neq 1 \vee \text{distinct-mset } m$
by (*metis* (*full-types*) *distinct-mset-def*)
then have *count* ($A + B$) (*aa* A) = 1 $\vee \text{distinct-mset } A$
using *dist* **by** (*meson* *mset-leD* *mset-le-add-left*)
then show *?thesis*
using *f2* **by** (*metis* (*no-types*) *One-nat-def* *add-is-1* *count-union* *mem-Collect-eq* *order-less-irrefl* *set-mset-def*)

qed

lemma *distinct-mset-minus[simp]*:
distinct-mset $A \Longrightarrow \text{distinct-mset } (A - B)$
by (*metis* *Multiset.diff-le-self* *mset-le-exists-conv* *distinct-mset-union*)

lemma *in-distinct-mset-set-distinct-mset*:
 $a \in \Sigma \Longrightarrow \text{distinct-mset-set } \Sigma \Longrightarrow \text{distinct-mset } a$
unfolding *distinct-mset-set-def* **by** *auto*

lemma *distinct-mset-remdups-mset[simp]*: *distinct-mset* (*remdups-mset* S)
using *count-remdups-mset-eq-1* **unfolding** *distinct-mset-def* **by** *metis*

lemma *distinct-mset-distinct[simp]*:
distinct-mset (*mset* x) = *distinct* x

unfolding *distinct-mset-def* **by** (auto simp: *distinct-count-atmost-1 not-in-iff*[*symmetric*])

lemma *distinct-mset-mset-set*:

distinct-mset (*mset-set* *A*)

unfolding *distinct-mset-def count-mset-set-if* **by** (auto simp: *not-in-iff*)

lemma *distinct-mset-rempdups-union-mset*:

assumes *distinct-mset* *A* **and** *distinct-mset* *B*

shows $A \# \cup B = \text{remdups-mset } (A + B)$

using *assms nat-le-linear* **unfolding** *remdups-mset-def*

by (force simp add: *multiset-eq-iff max-def count-mset-set-if distinct-mset-def not-in-iff*)

lemma *distinct-mset-set-distinct*:

distinct-mset-set (*mset* ' *set* *Cs*) $\longleftrightarrow (\forall c \in \text{set } Cs. \text{distinct } c)$

unfolding *distinct-mset-set-def* **by** auto

lemma *distinct-mset-add-single*:

distinct-mset ($\{\#a\# \} + L$) $\longleftrightarrow \text{distinct-mset } L \wedge a \notin \# L$

unfolding *distinct-mset-def*

apply (rule *iffI*)

prefer 2 **apply** (auto simp: *not-in-iff*)[]

apply *standard*

apply (*intro allI*)

apply (*rename-tac aa, case-tac a = aa*)

by (auto split: *if-split-asm*)

lemma *distinct-mset-single-add*:

distinct-mset ($L + \{\#a\# \}$) $\longleftrightarrow \text{distinct-mset } L \wedge a \notin \# L$

unfolding *add.commute*[of $L \{\#a\# \}$] *distinct-mset-add-single* **by** *fast*

lemma *distinct-mset-size-eq-card*:

distinct-mset *C* $\implies \text{size } C = \text{card } (\text{set-mset } C)$

by (*induction C*) (auto simp: *distinct-mset-single-add*)

Another characterisation of *distinct-mset*

lemma *distinct-mset-count-less-1*:

distinct-mset *S* $\longleftrightarrow (\forall a. \text{count } S a \leq 1)$

using *eq-iff nat-le-linear* **unfolding** *distinct-mset-def* **by** *fastforce*

lemma *distinct-mset-add*:

distinct-mset ($L + L'$) $\longleftrightarrow \text{distinct-mset } L \wedge \text{distinct-mset } L' \wedge L \# \cap L' = \{\#\}$ (is ?*A* \longleftrightarrow ?*B*)

proof (rule *iffI*)

assume ?*A*

have *L*: *distinct-mset* *L*

using $\langle \text{distinct-mset } (L + L') \rangle$ *distinct-mset-union* **by** *blast*

moreover **have** *L'*: *distinct-mset* *L'*

using $\langle \text{distinct-mset } (L + L') \rangle$ *distinct-mset-union* **unfolding** *add.commute*[of *L L'*] **by** *blast*

moreover **have** $L \# \cap L' = \{\#\}$

using $L \ L' \langle ?A \rangle$ **unfolding** *multiset-inter-def multiset-eq-iff distinct-mset-count-less-1*

by (*metis* *Nat.diff-le-self add-diff-cancel-left' count-diff count-empty diff-is-0-eq eq-iff le-neq-implies-less less-one*)

ultimately show ?*B* **by** *fast*

next

assume ?*B*

show ?*A*

unfolding *distinct-mset-count-less-1*

```

proof (intro allI)
  fix a
  have count (L + L') a ≤ count L a + count L' a
    by auto
  moreover have count L a + count L' a ≤ 1
    using (?B) by (metis One-nat-def add.commute add-decreasing2 count-diff diff-add-zero
      distinct-mset-count-less-1 le-SucE multiset-inter-count plus-multiset.rep-eq
      subset-mset.inf.idem)
  ultimately show count (L + L') a ≤ 1
    by arith
qed
qed

lemma distinct-mset-set-mset-ident[simp]: distinct-mset M  $\implies$  mset-set (set-mset M) = M
  apply (auto simp: multiset-eq-iff)
  apply (rename-tac x)
  apply (case-tac count M x = 0)
  apply (simp add: not-in-iff[symmetric])
  apply (case-tac count M x = 1)
  apply (simp add: count-inI)
  unfolding distinct-mset-count-less-1 by (meson le-neq-implies-less less-one)

lemma distinct-finite-set-mset-subseteq-iff[iff]:
  assumes dist: distinct-mset M and fin: finite N
  shows set-mset M  $\subseteq$  N  $\longleftrightarrow$  M  $\subseteq$  # mset-set N
proof
  assume set-mset M  $\subseteq$  N
  then show M  $\subseteq$  # mset-set N
    by (metis dist distinct-mset-set-mset-ident fin finite-subset mset-set-subseteq-mset-set)
next
  assume M  $\subseteq$  # mset-set N
  then show set-mset M  $\subseteq$  N
    by (metis contra-subsetD empty-iff finite-set-mset-mset-set infinite-set-mset-mset-set
      set-mset-mono subsetI)
qed

lemma distinct-mem-diff-mset:
  assumes dist: distinct-mset M and mem: x ∈ set-mset (M - N)
  shows x ∉ set-mset N
proof -
  have count M x = 1
    using dist mem by (meson distinct-mset-def in-diffD)
  then show ?thesis
    using mem by (metis count-greater-eq-one-iff in-diff-count not-less)
qed

lemma distinct-set-mset-eq:
  assumes
    dist-m: distinct-mset M and
    dist-n: distinct-mset N and
    set-eq: set-mset M = set-mset N
  shows M = N
proof -
  have mset-set (set-mset M) = mset-set (set-mset N)
    using set-eq by simp
  thus ?thesis

```

using *dist-m dist-n* by *auto*
qed

lemma *distinct-mset-union-mset*:

assumes
 distinct-mset D and
 distinct-mset C
shows *distinct-mset (D # \cup C)*
using *assms unfolding distinct-mset-count-less-1* by *force*

lemma *distinct-mset-inter-mset*:

assumes
 distinct-mset D and
 distinct-mset C
shows *distinct-mset (D # \cap C)*
using *assms unfolding distinct-mset-count-less-1*
by (*meson dual-order.trans subset-mset.inf-le2 subseteq-mset-def*)

lemma *distinct-mset-remove1-All*:

distinct-mset C \implies remove1-mset L C = removeAll-mset L C
by (*auto simp: multiset-eq-iff distinct-mset-count-less-1*)

lemma *distinct-mset-size-2*: *distinct-mset {#a, b#} \longleftrightarrow a \neq b*
unfolding *distinct-mset-def* by *auto*

1.1.9 Filter

lemma *mset-filter-compl*: *mset (filter p xs) + mset (filter (Not \circ p) xs) = mset xs*
apply (*induct xs*)
by *simp*
 (*metis (no-types) add-diff-cancel-left' comp-apply filter.simps(2) mset.simps(2)*
 mset-compl-union)

lemma *image-mset-subseteq-mono*: *A \subseteq # B \implies image-mset f A \subseteq # image-mset f B*
by (*metis image-mset-union subset-mset.le-iff-add*)

lemma *image-filter-ne-mset*[*simp*]:

image-mset f {#x \in # M. f x \neq y#} = removeAll-mset y (image-mset f M)
by (*induct M, auto, meson count-le-replicate-mset-le order-refl subset-mset.add-diff-assoc2*)

lemma *comprehension-mset-False*[*simp*]:

{# L \in # A. False#} = {#}
by (*auto simp: multiset-eq-iff*)

Near duplicate of *filter-eq-replicate-mset*: *{# y \in # ?D. y = ?x#} = replicate-mset (count ?D ?x) ?x*.

lemma *filter-mset-eq*:

filter-mset (op = L) A = replicate-mset (count A L) L
by (*auto simp: multiset-eq-iff*)

lemma *filter-mset-union-mset*:

filter-mset P (A # \cup B) = filter-mset P A # \cup filter-mset P B
by (*auto simp: multiset-eq-iff*)

lemma *filter-mset-mset-set*:

finite A \implies filter-mset P (mset-set A) = mset-set {a \in A. P a}

by (auto simp: multiset-eq-iff count-mset-set-if)

See *filter-cong* for the set version. Mark as *[fundef-cong]* too?

lemma *filter-mset-cong*:
 assumes $[simp]: M = M'$ and $[simp]: \bigwedge a. a \in \# M \implies P a = Q a$
 shows $filter\text{-}mset\ P\ M = filter\text{-}mset\ Q\ M$
proof –
 have $M - filter\text{-}mset\ Q\ M = filter\text{-}mset\ (\lambda a. \neg Q a)\ M$
 by (subst multiset-partition[of - Q]) simp
 then show ?thesis
 by (auto simp: filter-mset-eq-conv)
qed

1.1.10 Sums

lemma *msetsum-distrib* $[simp]$:
 fixes $C\ D :: 'a \Rightarrow 'b :: \{comm\text{-}monoid\text{-}add\}$
 shows $(\sum x \in \# A. C\ x + D\ x) = (\sum x \in \# A. C\ x) + (\sum x \in \# A. D\ x)$
 by (induction A) (auto simp: ac-simps)

lemma *msetsum-union-disjoint*:
 assumes $A \# \cap B = \{\#\}$
 shows $(\sum La \in \# A \# \cup B. f\ La) = (\sum La \in \# A. f\ La) + (\sum La \in \# B. f\ La)$
 by (metis assms diff-zero empty-sup image-mset-union msetsum.union multiset-inter-commute
 multiset-union-diff-commute sup-subset-mset-def zero-diff)

1.1.11 Order

Instantiating multiset order as a linear order.

TODO: remove when multiset is of sort ord again

instantiation *multiset* :: $(linorder)\ linorder$
begin

definition *less-multiset* :: $'a :: linorder\ multiset \Rightarrow 'a\ multiset \Rightarrow bool$ **where**
 $M' < M \longleftrightarrow M' \# \subset \# M$

definition *less-eq-multiset* :: $'a\ multiset \Rightarrow 'a\ multiset \Rightarrow bool$ **where**
 $(M' :: 'a\ multiset) \leq M \longleftrightarrow M' \# \subseteq \# M$

instance
 by standard (auto simp add: less-eq-multiset-def less-multiset-def multiset-order.less-le-not-le
 add.commute multiset-order.add-right-mono)
end
end

1.2 Transitions

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

theory *Wellfounded-More*
imports *Main*

begin

1.2.1 More theorems about Closures

This is the equivalent of the theorem *rtranclp-mono* for *tranclp*

lemma *tranclp-mono-explicit*:

$r^{++} a b \implies r \leq s \implies s^{++} a b$
using *rtranclp-mono* **by** (*auto dest!*: *tranclpD intro: rtranclp-into-tranclp2*)

lemma *tranclp-mono*:

assumes *mono*: $r \leq s$
shows $r^{++} \leq s^{++}$
using *rtranclp-mono[OF mono]* *mono* **by** (*auto dest!*: *tranclpD intro: rtranclp-into-tranclp2*)

lemma *tranclp-idemp-rel*:

$R^{++++} a b \longleftrightarrow R^{++} a b$
apply (*rule iffI*)
prefer 2 **apply** *blast*
by (*induction rule: tranclp-induct*) *auto*

Equivalent of the theorem *rtranclp-idemp*

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

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

This theorem already exists as theroem *Nitpick.rtranclp-unfold* (and sledgehammer uses it), but it makes sense to duplicate it, because it is unclear how stable the lemmas in the `~~/src/HOL/Nitpick.thy` theory are.

lemma *rtranclp-unfold*: $rtranclp\ r\ a\ b \longleftrightarrow (a = b \vee tranclp\ r\ a\ b)$
by (*meson rtranclp.simps rtranclpD tranclp-into-rtranclp*)

lemma *tranclp-unfold-end*: $tranclp\ r\ a\ b \longleftrightarrow (\exists a'. rtranclp\ r\ a\ a' \wedge r\ a'\ b)$
by (*metis rtranclp.rtrancl-refl rtranclp-into-tranclp1 tranclp.cases tranclp-into-rtranclp*)

Near duplicate of theorem *tranclpD*:

lemma *tranclp-unfold-begin*: $tranclp\ r\ a\ b \longleftrightarrow (\exists a'. r\ a\ a' \wedge rtranclp\ r\ a'\ b)$
by (*meson rtranclp-into-tranclp2 tranclpD*)

lemma *trancl-set-tranclp*: $(a, b) \in \{(b, a). P\ a\ b\}^+ \longleftrightarrow P^{++}\ b\ a$
apply (*rule iffI*)
apply (*induction rule: trancl-induct; simp*)
apply (*induction rule: tranclp-induct; auto simp: trancl-into-trancl2*)
done

lemma *tranclp-rtranclp-rtranclp-rel*: $R^{+++}\ a\ b \longleftrightarrow R^{**}\ a\ b$
by (*simp add: rtranclp-unfold*)

lemma *tranclp-rtranclp-rtranclp[simp]*: $R^{+++} = R^{**}$
by (*fastforce simp: rtranclp-unfold*)

lemma *rtranclp-exists-last-with-prop*:

assumes $R\ x\ z$ **and** $R^{**}\ z\ z'$ **and** $P\ x\ z$
shows $\exists y\ y'. R^{**}\ x\ y \wedge R\ y\ y' \wedge P\ y\ y' \wedge (\lambda a\ b. R\ a\ b \wedge \neg P\ a\ b)^{**}\ y'\ z'$
using *assms(2,1,3)*

proof (*induction*)

```

case base
then show ?case by auto
next
case (step z' z'') note z = this(2) and IH = this(3)[OF 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.prems(2) apply auto[1]
      using IH z rtrancp.rtrancI-into-rtrancI by fastforce
qed

```

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

1.2.2 Full Transitions

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

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

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

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

We define output notations only for printing:

notation (**output**) *full1* $(-^{+\downarrow})$

notation (**output**) *full* $(-^{\downarrow})$

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

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

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

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

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

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

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

```

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

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

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

lemma rtranclp-full1-eq-or-full1:
   $(\text{full1 } R)^{**} a b \longleftrightarrow (a = b \vee \text{full1 } R a b)$ 
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  $aa :: ('a \Rightarrow 'a \Rightarrow \text{bool}) \Rightarrow 'a \Rightarrow 'a \Rightarrow 'a$  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  $\neg \text{full1 } R a b \wedge a \neq b$ 
      then have  $a \neq b \wedge a \neq b \wedge \neg \text{full1 } R (aa (\text{full1 } R) a b) b \vee \neg (\text{full1 } R)^{**} a b \wedge a \neq b$ 
        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:
   $(\text{full1 } R)^{++} a b \longleftrightarrow \text{full1 } R a b$ 
  by (metis full1-def rtranclp-full1-eq-or-full1 tranclp-unfold-begin)

```

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

```

```

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

```

1.2.4 More Well-Foundedness

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

- link between *wf* and infinite chains: theorems *wf-iff-no-infinite-down-chain* and *wf-no-infinite-down-chain*

```

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

```

```

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

```

```

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

```

```

lemma wf-wf-if-measure':
  assumes wf r and H:  $\bigwedge x\ y.\ P\ x \implies g\ x\ y \implies (f\ y, f\ x) \in r$ 
  shows  $wf\ \{(y, x).\ P\ x \wedge g\ x\ y\}$ 
proof –
  have  $wf\ \{(b, a).\ (f\ b, f\ a) \in r\}$  using assms(1) wf-if-measure-f by auto
  then have  $wf\ \{(b, a).\ P\ a \wedge g\ a\ b \wedge (f\ b, f\ a) \in r\}$ 
    using wf-subset[of - {(b, a). P a ∧ g a b ∧ (f b, f a) ∈ r}] by auto
  moreover have  $\{(b, a).\ P\ a \wedge g\ a\ b \wedge (f\ b, f\ a) \in r\} \subseteq \{(b, a).\ (f\ b, f\ a) \in r\}$  by auto

```

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

lemma *wf-lex-less*: *wf* (*lex* $\{(a, b). (a::nat) < b\}$)

proof –

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

qed

lemma *wfP-if-measure2*: fixes $f :: 'a \Rightarrow nat$

shows $(\bigwedge x\ y. P\ x\ y \implies g\ x\ y \implies f\ x < f\ y) \implies \text{wf } \{(x, y). P\ x\ y \wedge g\ x\ y\}$

apply(*insert wf-measure[of f]*)

apply(*simp only: measure-def inv-image-def less-than-def less-eq*)

apply(*erule wf-subset*)

apply *auto*

done

lemma *lexord-on-finite-set-is-wf*:

assumes

P-finite: $\bigwedge U. P\ U \longrightarrow U \in A$ and

finite: *finite* A and

wf: *wf* R and

trans: *trans* R

shows *wf* $\{(T, S). (P\ S \wedge P\ T) \wedge (T, S) \in \text{lexord } R\}$

proof (*rule wfP-if-measure2*)

fix $T\ S$

assume $P: P\ S \wedge P\ T$ and

s-le-t: $(T, S) \in \text{lexord } R$

let $?f = \lambda S. \{U. (U, S) \in \text{lexord } R \wedge P\ U \wedge P\ S\}$

have $?f\ T \subseteq ?f\ S$

using *s-le-t* P *lexord-trans* *trans* by *auto*

moreover have $T \in ?f\ S$

using *s-le-t* P by *auto*

moreover have $T \notin ?f\ T$

using *s-le-t* by (*auto simp add: lexord-irreflexive local.wf*)

ultimately have $\{U. (U, T) \in \text{lexord } R \wedge P\ U \wedge P\ T\} \subset \{U. (U, S) \in \text{lexord } R \wedge P\ U \wedge P\ S\}$
by *auto*

moreover have *finite* $\{U. (U, S) \in \text{lexord } R \wedge P\ U \wedge P\ S\}$

using *finite* by (*metis (no-types, lifting) P-finite finite-subset mem-Collect-eq subsetI*)

ultimately show $\text{card } (?f\ T) < \text{card } (?f\ S)$ 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  $\Rightarrow$  bool and x :: 'c  $\times$  'a
      assume H:  $\forall x. (\forall y. (y, x) \in \{((M', N'), M, y). R N' y\} \longrightarrow P y) \longrightarrow P x$ 
      obtain a b where x: x = (a, b) by (cases x)
      have P: P x = (P  $\circ$  ( $\lambda(a, b). (b, a)$ )) (b, a)
        unfolding x by auto
      show P x
        using wf[of P  $\circ$  ( $\lambda(a, b). (b, a)$ )] apply rule
        using H apply simp
        unfolding P by blast
    qed
  qed

```

```

lemma wf-if-measure-f-notation2:
  assumes wf r
  shows wf  $\{(b, h a) \mid b a. (f b, f (h a)) \in r\}$ 
  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  $\{(y, h x) \mid y x. P x \wedge g x y\}$ 
proof -
  have wf  $\{(b, h a) \mid b a. (f b, f (h a)) \in r\}$  using assms(1) wf-if-measure-f-notation2 by auto
  then have wf  $\{(b, h a) \mid b a. P a \wedge g a b \wedge (f b, f (h a)) \in r\}$ 
    using wf-subset[of -  $\{(b, h a) \mid b a. P a \wedge g a b \wedge (f b, f (h a)) \in r\}$ ] by auto
  moreover have  $\{(b, h a) \mid b a. P a \wedge g a b \wedge (f b, f (h a)) \in r\}$ 
     $\subseteq \{(b, h a) \mid b a. (f b, f (h a)) \in r\}$  by auto
  moreover have  $\{(b, h a) \mid b a. P a \wedge g a b \wedge (f b, f (h a)) \in r\} = \{(b, h a) \mid b a. P a \wedge g a b\}$ 
    using H by auto
  ultimately show ?thesis using wf-subset by simp
qed

```

```

end
theory List-More
imports Main ../lib/Multiset-More
begin

```

```

Sledgehammer parameters
sledgehammer-params[debug]

```

1.3 Various Lemmas

Close to the theorem *nat-less-induct* ($(\bigwedge n. \forall m < n. ?P m \implies ?P n) \implies ?P n$), but with a separation between the zero and non-zero case.

```

thm nat-less-induct

```

```

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

```

This is only proved in simple cases by auto. In assumptions, nothing happens, and the theorem *if-split-asm* can blow up goals (because of other if-expressions either in the context or as simplification rules).

```

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

```

Bounded function have not yet been defined in Isabelle.

```

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

```

```

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

```

```

lemma not-bounded-nat-exists-larger:
  fixes  $f :: \text{nat} \Rightarrow \text{nat}$ 
  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  $\leq n_0$ )
    apply (metis (mono-tags, lifting) Max-ge Un-insert-right  $\langle \text{finite } \{f\ n \mid n. n \leq n_0\} \rangle$ 
      finite-insert insertCI mem-Collect-eq sup-bot.right-neutral)
    by (metis (no-types, lifting)  $H$  Max-less-iff Un-insert-right  $\langle \text{finite } \{f\ n \mid n. n \leq n_0\} \rangle$ 
      finite-insert insertI1 insert-not-empty leI sup-bot.right-neutral)
  then show False
    using unbound unfolding bounded-def by auto
qed

```

A function is bounded iff its product with a non-zero constant is bounded. The non-zero condition is needed only for the reverse implication (see for example $k = 0$ and $f = (\lambda i. i)$ for a counter-example).

```

lemma bounded-const-product:
  fixes  $k :: \text{nat}$  and  $f :: \text{nat} \Rightarrow \text{nat}$ 
  assumes  $k > 0$ 
  shows  $\text{bounded } f \longleftrightarrow \text{bounded } (\lambda i. k * f\ i)$ 
  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 property that can be expected from *bounded* holds.

```

lemma bounded-finite-linorder:

```



```

fixes  $f :: 'a \Rightarrow 'a :: \{finite, linorder\}$ 
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

```

1.4 More List

1.4.1 *upt*

The simplification rules are not very handy, because theorem *upt.simps (2)* (i.e. $[?i..<Suc\ ?j] = (if\ ?i \leq\ ?j\ then\ [?i..<?j]\ @\ [?j]\ else\ [])$) leads to a case distinction, that we do not want if the condition is not in the context.

```

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

```

```

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

```

```

declare upt.simps(2)[simp del]

```

The counterpart for this lemma when $n - m < i$ is theorem *take-all*. It is close to theorem *?i + ?m ≤ ?n $\implies take\ ?m\ [?i..<?n] = [?i..<?i + ?m]$* , but seems more general.

```

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

```

```

lemma append-cons-eq-upt:
  assumes  $A @ B = [m..<n]$ 
  shows  $A = [m ..<m+length\ A]$  and  $B = [m + length\ A..<n]$ 

```

```

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

```

The converse of theorem *append-cons-eq-upt* does not hold, for example if @ term "B:: nat list" is empty and A is $[0::'a]$:

```

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

```

oops

A more restrictive version holds:

```

lemma  $B \neq [] \implies A @ B = [m..<n] \longleftrightarrow A = [m ..<m+length\ A] \wedge B = [m + length\ A..<n]$ 
  (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.prem1 append-cons-eq-upt-length-i upt-eq-Cons-conv)
  with Cons.IH[OF A] show ?case by auto
qed

lemma append-cons-eq-upt-length-i-end:
  assumes  $A @ i \# B = [m..<n]$ 
  shows  $B = [\text{Suc } i..<n]$ 
proof -
  have  $B = [\text{Suc } m + \text{length } A..<n]$  using assms append-cons-eq-upt[of  $A @ [i] B m n$ ] by auto
  have  $(A @ i \# B) ! (\text{length } A) = i$  by auto
  moreover have  $n - m = \text{length } (A @ i \# B)$ 
    using assms length-upt by auto
  then have  $[m..<n] ! (\text{length } A) = m + \text{length } A$  by simp
  ultimately have  $i = m + \text{length } A$  using assms by auto
  then show ?thesis using  $\langle B = [\text{Suc } m + \text{length } A..<n] \rangle$  by auto
qed

lemma Max-n-upt:  $\text{Max } (\text{insert } 0 \{ \text{Suc } 0..<n \}) = n - \text{Suc } 0$ 
proof (induct n)
  case 0
  then show ?case by simp
next
  case (Suc n)
  note IH = this
  have  $i : \text{insert } 0 \{ \text{Suc } 0..<\text{Suc } n \} = \text{insert } 0 \{ \text{Suc } 0..<n \} \cup \{ n \}$  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

```

The following two lemmas are useful as simp rules for case-distinction. The case $length\ l = 0$ is already simplified by default.

```

lemma length-list-Suc-0:
   $length\ W = Suc\ 0 \longleftrightarrow (\exists L. W = [L])$ 
apply (cases  $W$ )
apply simp
apply (rename-tac  $a\ W'$ , case-tac  $W'$ )
apply auto
done

```

```

lemma length-list-2:  $length\ S = 2 \longleftrightarrow (\exists a\ b. S = [a, b])$ 
apply (cases  $S$ )
apply simp
apply (rename-tac  $a\ S'$ )
apply (case-tac  $S'$ )
by simp-all

```

```

lemma finite-bounded-list:
  fixes  $b :: nat$ 
  shows finite  $\{xs. length\ xs < s \wedge (\forall i < length\ xs. xs\ !\ i < b)\}$  (is finite (?S s))
proof (induction  $s$ )
  case 0
    then show ?case by auto
  next
    case (Suc  $s$ ) note IH = this(1)
    have  $H$ : ?S (Suc  $s$ )  $\subseteq$  ?S  $s \cup \{x \# xs \mid x\ xs. x < b \wedge length\ xs < s \wedge (\forall i < length\ xs. xs\ !\ i < b)\}$ 
       $\cup \{\}\}$ 
      (is -  $\subseteq$  -  $\cup$  ?C  $\cup$  -)
    proof
      fix  $xs$ 
      assume  $xs \in ?S\ (Suc\ s)$ 
      then have  $B$ :  $\forall i < length\ xs. xs\ !\ i < b$  and  $len$ :  $length\ xs < Suc\ s$ 
        by auto
      consider
        ( $st$ )  $length\ xs < s$  |
        ( $s$ )  $length\ xs = 0$  and  $s = 0$  |
        ( $s'$ )  $s'$  where  $length\ xs = Suc\ s'$ 
      using  $len$  by (cases  $s$ ) (auto simp add: Nat.less-Suc-eq)
    then show  $xs \in ?S\ s \cup ?C \cup \{\}\}$ 
      proof cases
        case  $st$ 
          then show ?thesis using  $B$  by auto
        next
          case  $s$ 
            then show ?thesis using  $B$  by auto
        next

```

```

      case s' note len-xs = this(1)
      then obtain x xs' where xs: xs = x # xs' by (cases xs) auto
      then show ?thesis using len-xs B len s' unfolding xs by auto
    qed
  qed
  have ?C ⊆ (case-prod Cons) ‘ ({x. x < b} × ?S s)
  by auto
  moreover have finite ({x. x < b} × ?S s)
  using IH by (auto simp: finite-cartesian-product-iff)
  ultimately have finite ?C by (simp add: finite-surj)
  then have finite (?S s ∪ ?C ∪ {[]})
  using IH by auto
  then show ?case using H by (auto intro: finite-subset)
qed

```

1.4.2 Lexicographic Ordering

lemma *lexn-Suc*:

```

(x # xs, y # ys) ∈ lexn r (Suc n) ⟷
(length xs = n ∧ length ys = n) ∧ ((x, y) ∈ r ∨ (x = y ∧ (xs, ys) ∈ lexn r n))
by (auto simp: map-prod-def image-iff lex-prod-def)

```

lemma *lexn-n*:

```

n > 0 ⟹ (x # xs, y # ys) ∈ lexn r n ⟷
(length xs = n-1 ∧ length ys = n-1) ∧ ((x, y) ∈ r ∨ (x = y ∧ (xs, ys) ∈ lexn r (n - 1)))
apply (cases n)
apply simp
by (auto simp: map-prod-def image-iff lex-prod-def)

```

There is some subtle point in the proof here. *1* is converted to *Suc 0*, but *2* is not: meaning that *1* is automatically simplified by default using the default simplification rule *lexn.simps*. However, the latter needs additional simplification rule (see the proof of the theorem above).

lemma *lexn2-conv*:

```

([a, b], [c, d]) ∈ lexn r 2 ⟷ (a, c) ∈ r ∨ (a = c ∧ (b, d) ∈ r)
by (auto simp: lexn-n simp del: lexn.simps(2))

```

lemma *lexn3-conv*:

```

([a, b, c], [a', b', c']) ∈ lexn r 3 ⟷
(a, a') ∈ r ∨ (a = a' ∧ (b, b') ∈ r) ∨ (a = a' ∧ b = b' ∧ (c, c') ∈ r)
by (auto simp: lexn-n simp del: lexn.simps(2))

```

1.4.3 Remove

More lemmas about remove

lemma *remove1-Nil*:

```

remove1 (- L) W = [] ⟷ (W = [] ∨ W = [-L])
by (cases W) auto

```

lemma *remove1-mset-single-add*:

```

a ≠ b ⟹ remove1-mset a ({#b#} + C) = {#b#} + remove1-mset a C
remove1-mset a ({#a#} + C) = C
by (auto simp: multiset-eq-iff)

```

Remove under condition

This function removes the first element such that the condition f holds. It generalises *remove1*.

```
fun remove1-cond where  
remove1-cond  $f$  [] = [] |  
remove1-cond  $f$  ( $C' \# L$ ) = (if  $f C'$  then  $L$  else  $C' \#$  remove1-cond  $f$   $L$ )
```

```
lemma remove1  $x$   $xs$  = remove1-cond (( $op =$ )  $x$ )  $xs$   
by (induction  $xs$ ) auto
```

```
lemma mset-map-mset-remove1-cond:  
mset (map mset (remove1-cond ( $\lambda L$ . mset  $L =$  mset  $a$ )  $C$ )) =  
remove1-mset (mset  $a$ ) (mset (map mset  $C$ ))  
by (induction  $C$ ) (auto simp: ac-simps remove1-mset-single-add)
```

We can also generalise *removeAll*, which is close to *filter*:

```
fun removeAll-cond where  
removeAll-cond  $f$  [] = [] |  
removeAll-cond  $f$  ( $C' \# L$ ) =  
(if  $f C'$  then removeAll-cond  $f$   $L$  else  $C' \#$  removeAll-cond  $f$   $L$ )
```

```
lemma removeAll  $x$   $xs$  = removeAll-cond (( $op =$ )  $x$ )  $xs$   
by (induction  $xs$ ) auto
```

```
lemma removeAll-cond  $P$   $xs$  = filter ( $\lambda x$ .  $\neg P$   $x$ )  $xs$   
by (induction  $xs$ ) auto
```

```
lemma mset-map-mset-removeAll-cond:  
mset (map mset (removeAll-cond ( $\lambda b$ . mset  $b =$  mset  $a$ )  $C$ ))  
= removeAll-mset (mset  $a$ ) (mset (map mset  $C$ ))  
by (induction  $C$ ) (auto simp: ac-simps mset-less-eqI multiset-diff-union-assoc)
```

The definition and the correctness theorem are from the multiset theory `~~/src/HOL/Library/Multiset.thy`, but a name is necessary to refer to them:

```
abbreviation union-mset-list where  
union-mset-list  $xs$   $ys$   $\equiv$  case-prod append (fold ( $\lambda x$  ( $ys$ ,  $zs$ ). (remove1  $x$   $ys$ ,  $x \#$   $zs$ ))  $xs$  ( $ys$ , []))
```

```
lemma union-mset-list:  
mset  $xs \# \cup$  mset  $ys$  = mset (union-mset-list  $xs$   $ys$ )  
proof –  
have  $\bigwedge zs$ . mset (case-prod append (fold ( $\lambda x$  ( $ys$ ,  $zs$ ). (remove1  $x$   $ys$ ,  $x \#$   $zs$ ))  $xs$  ( $ys$ ,  $zs$ ))) =  
  (mset  $xs \# \cup$  mset  $ys$ ) + mset  $zs$   
  by (induct  $xs$  arbitrary:  $ys$ ) (simp-all add: multiset-eq-iff)  
then show ?thesis by simp  
qed
```

Filter

```
lemma distinct-filter-eq-if:  
distinct  $C \implies$  length (filter ( $op =$   $L$ )  $C$ ) = (if  $L \in$  set  $C$  then 1 else 0)  
by (induction  $C$ ) auto
```

end

Chapter 2

Definition of Entailment

This chapter defines various form of entailment.

end

2.1 Clausal Logic

```
theory Clausal-Logic
imports ../lib/Multiset-More
begin
```

Resolution operates of clauses, which are disjunctions of literals. The material formalized here corresponds roughly to Sections 2.1 (“Formulas and Clauses”) of Bachmair and Ganzinger, excluding the formula and term syntax.

2.1.1 Literals

Literals consist of a polarity (positive or negative) and an atom, of type *'a*.

```
datatype 'a literal =
  is-pos: Pos (atm-of: 'a)
| Neg (atm-of: 'a)
```

```
abbreviation is-neg :: 'a literal  $\Rightarrow$  bool where is-neg L  $\equiv \neg$  is-pos L
```

```
lemma Pos-atm-of-iff[simp]: Pos (atm-of L) = L  $\longleftrightarrow$  is-pos L
by auto (metis literal.disc(1))
```

```
lemma Neg-atm-of-iff[simp]: Neg (atm-of L) = L  $\longleftrightarrow$  is-neg L
by auto (metis literal.disc(2))
```

```
lemma ex-lit-cases:  $(\exists L. P L) \longleftrightarrow (\exists A. P (Pos A) \vee P (Neg A))$ 
by (metis literal.exhaust)
```

```
instantiation literal :: (type) uminus
begin
```

```
definition uminus-literal :: 'a literal  $\Rightarrow$  'a literal where
  uminus L = (if is-pos L then Neg else Pos) (atm-of L)
```

```
instance ..
```

end

lemma

uminus-Pos[simp]: $- \text{Pos } A = \text{Neg } A$ and
uminus-Neg[simp]: $- \text{Neg } A = \text{Pos } A$
unfolding *uminus-literal-def* **by** *simp-all*

lemma *atm-of-uminus[simp]:*

atm-of $(-L) = \text{atm-of } L$
by (*case-tac L, auto*)

lemma *uminus-of-uminus-id[simp]:*

$- (- (x:: 'v \text{ literal})) = x$
by (*simp add: uminus-literal-def*)

lemma *uminus-not-id[simp]:*

$x \neq - (x:: 'v \text{ literal})$
by (*case-tac x, auto*)

lemma *uminus-not-id'[simp]:*

$- x \neq (x:: 'v \text{ literal})$
by (*case-tac x, auto*)

lemma *uminus-eq-inj[iff]:*

$-(a:: 'v \text{ literal}) = -b \iff a = b$
by (*case-tac a; case-tac b*) *auto+*

lemma *uminus-lit-swap:*

$(a:: 'a \text{ literal}) = -b \iff -a = b$
by *auto*

instantiation *literal :: (preorder) preorder*

begin

definition *less-literal :: 'a literal \Rightarrow 'a literal \Rightarrow bool where*

less-literal L M $\iff \text{atm-of } L < \text{atm-of } M \vee \text{atm-of } L \leq \text{atm-of } M \wedge \text{is-neg } L < \text{is-neg } M$

definition *less-eq-literal :: 'a literal \Rightarrow 'a literal \Rightarrow bool where*

less-eq-literal L M $\iff \text{atm-of } L < \text{atm-of } M \vee \text{atm-of } L \leq \text{atm-of } M \wedge \text{is-neg } L \leq \text{is-neg } M$

instance

apply *intro-classes*

unfolding *less-literal-def less-eq-literal-def* **by** (*auto intro: order-trans simp: less-le-not-le*)

end

instantiation *literal :: (order) order*

begin

instance

apply *intro-classes*

unfolding *less-eq-literal-def* **by** (*auto intro: literal.expand*)

end

lemma *pos-less-neg[simp]: $\text{Pos } A < \text{Neg } A$*


```

unfolding less-literal-def by simp

lemma pos-less-pos-iff[simp]:  $Pos\ A < Pos\ B \longleftrightarrow A < B$ 
unfolding less-literal-def by simp

lemma pos-less-neg-iff[simp]:  $Pos\ A < Neg\ B \longleftrightarrow A \leq B$ 
unfolding less-literal-def by (auto simp: less-le-not-le)

lemma neg-less-pos-iff[simp]:  $Neg\ A < Pos\ B \longleftrightarrow A < B$ 
unfolding less-literal-def by simp

lemma neg-less-neg-iff[simp]:  $Neg\ A < Neg\ B \longleftrightarrow A < B$ 
unfolding less-literal-def by simp

lemma pos-le-neg[simp]:  $Pos\ A \leq Neg\ A$ 
unfolding less-eq-literal-def by simp

lemma pos-le-pos-iff[simp]:  $Pos\ A \leq Pos\ B \longleftrightarrow A \leq B$ 
unfolding less-eq-literal-def by (auto simp: less-le-not-le)

lemma pos-le-neg-iff[simp]:  $Pos\ A \leq Neg\ B \longleftrightarrow A \leq B$ 
unfolding less-eq-literal-def by (auto simp: less-imp-le)

lemma neg-le-pos-iff[simp]:  $Neg\ A \leq Pos\ B \longleftrightarrow A < B$ 
unfolding less-eq-literal-def by simp

lemma neg-le-neg-iff[simp]:  $Neg\ A \leq Neg\ B \longleftrightarrow A \leq B$ 
unfolding less-eq-literal-def by (auto simp: less-imp-le)

lemma leq-imp-less-eq-atm-of:  $L \leq M \implies atm\text{-}of\ L \leq atm\text{-}of\ M$ 
by (metis less-eq-literal-def less-le-not-le)

instantiation literal :: (linorder) linorder
begin

instance
  apply intro-classes
  unfolding less-eq-literal-def less-literal-def by auto

end

instantiation literal :: (wellorder) wellorder
begin

instance
proof intro-classes
  fix  $P :: 'a\ literal \Rightarrow bool$  and  $L :: 'a\ literal$ 
  assume ih:  $\bigwedge L. (\bigwedge M. M < L \implies P\ M) \implies P\ L$ 
  have  $\bigwedge x. (\bigwedge y. y < x \implies P\ (Pos\ y) \wedge P\ (Neg\ y)) \implies P\ (Pos\ x) \wedge P\ (Neg\ x)$ 
    by (rule conjI[OF ih ih])
    (auto simp: less-literal-def atm-of-def split: literal.splits intro: ih)
  hence  $\bigwedge A. P\ (Pos\ A) \wedge P\ (Neg\ A)$ 
    by (rule less-induct) blast
  thus  $P\ L$ 
    by (cases  $L$ ) simp
qed

```

end

2.1.2 Clauses

Clauses are (finite) multisets of literals.

type-synonym 'a clause = 'a literal multiset

abbreviation poss :: 'a multiset \Rightarrow 'a clause **where** poss AA $\equiv \{\#Pos\ A.\ A \in \# AA\}$

abbreviation negs :: 'a multiset \Rightarrow 'a clause **where** negs AA $\equiv \{\#Neg\ A.\ A \in \# AA\}$

lemma image-replicate-mset[simp]: $\{\#f\ A.\ A \in \# replicate_mset\ n\ A\} = replicate_mset\ n\ (f\ A)$
by (induct n) (simp, subst replicate-mset-Suc, simp)

lemma Max-in-lits: $C \neq \{\#\} \implies Max\ (set_mset\ C) \in \# C$
by (rule Max-in[OF finite-set-mset, unfolded set-mset-eq-empty-iff])

lemma Max-atm-of-set-mset-commute: $C \neq \{\#\} \implies Max\ (atm_of\ 'set_mset\ C) = atm_of\ (Max\ (set_mset\ C))$
by (rule mono-Max-commute[symmetric])
 (auto simp: mono-def atm-of-def less-eq-literal-def less-literal-def)

lemma Max-pos-neg-less-multiset:
assumes max: $Max\ (set_mset\ C) = Pos\ A$ **and** neg: $Neg\ A \in \# D$
shows $C \# \subseteq \# D$

proof –

have $Max\ (set_mset\ C) < Neg\ A$

using max **by** simp

thus ?thesis

using neg **by** (metis (no-types) ex-gt-imp-less-multiset Max-less-iff[OF finite-set-mset]
 all-not-in-conv)

qed

lemma pos-Max-imp-neg-notin: $Max\ (set_mset\ C) = Pos\ A \implies Neg\ A \notin \# C$
using Max-pos-neg-less-multiset[unfolded multiset-linorder.not-le[symmetric]] **by** blast

lemma less-eq-Max-lit: $C \neq \{\#\} \implies C \# \subseteq \# D \implies Max\ (set_mset\ C) \leq Max\ (set_mset\ D)$

proof (unfold le-multiset_{HO})

assume ne: $C \neq \{\#\}$ **and** ex-gt: $\forall x. count\ D\ x < count\ C\ x \longrightarrow (\exists y > x. count\ C\ y < count\ D\ y)$

from ne **have** $Max\ (set_mset\ C) \in \# C$

by (fast intro: Max-in-lits)

hence $\exists l. l \in \# D \wedge \neg l < Max\ (set_mset\ C)$

using ex-gt **by** (metis count-greater-zero-iff count-inI less-not-sym)

hence $\neg Max\ (set_mset\ D) < Max\ (set_mset\ C)$

by (metis Max.coboundedI[OF finite-set-mset] le-less-trans)

thus ?thesis

by simp

qed

definition atms-of :: 'a clause \Rightarrow 'a set **where**
 atms-of C = atm-of 'set-mset C

lemma atms-of-empty[simp]: $atms_of\ \{\#\} = \{\}$
unfolding atms-of-def **by** simp

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

lemma *atms-of-union-mset[simp]*:
 $\text{atms-of } (A \# \cup B) = \text{atms-of } A \cup \text{atms-of } B$
unfolding *atms-of-def* **by** (*auto simp: max-def split: if-split-asm*)

lemma *finite-atms-of[iff]*: *finite* ($\text{atms-of } C$)
unfolding *atms-of-def* **by** *simp*

lemma *atm-of-lit-in-atms-of*: $L \in \# C \implies \text{atm-of } L \in \text{atms-of } C$
unfolding *atms-of-def* **by** *simp*

lemma *atms-of-plus[simp]*: $\text{atms-of } (C + D) = \text{atms-of } C \cup \text{atms-of } D$
unfolding *atms-of-def image-def* **by** *auto*

lemma *pos-lit-in-atms-of*: $\text{Pos } A \in \# C \implies A \in \text{atms-of } C$
unfolding *atms-of-def* **by** (*metis image-iff literal.sel(1)*)

lemma *neg-lit-in-atms-of*: $\text{Neg } A \in \# C \implies A \in \text{atms-of } C$
unfolding *atms-of-def* **by** (*metis image-iff literal.sel(2)*)

lemma *atm-imp-pos-or-neg-lit*: $A \in \text{atms-of } C \implies \text{Pos } A \in \# C \vee \text{Neg } A \in \# C$
unfolding *atms-of-def image-def mem-Collect-eq*
by (*metis Neg-atm-of-iff Pos-atm-of-iff*)

lemma *atm-iff-pos-or-neg-lit*: $A \in \text{atms-of } L \longleftrightarrow \text{Pos } A \in \# L \vee \text{Neg } A \in \# L$
by (*auto intro: pos-lit-in-atms-of neg-lit-in-atms-of dest: atm-imp-pos-or-neg-lit*)

lemma *atm-of-eq-atm-of*:
 $\text{atm-of } L = \text{atm-of } L' \longleftrightarrow (L = L' \vee L = -L')$
by (*cases L; cases L'*) *auto*

lemma *atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set*:
 $\text{atm-of } L \in \text{atm-of } I \longleftrightarrow (L \in I \vee -L \in I)$
by (*auto intro: rev-image-eqI simp: atm-of-eq-atm-of*)

lemma *lits-subseteq-imp-atms-subseteq*: $\text{set-mset } C \subseteq \text{set-mset } D \implies \text{atms-of } C \subseteq \text{atms-of } D$
unfolding *atms-of-def* **by** *blast*

lemma *atms-empty-iff-empty[iff]*: $\text{atms-of } C = \{\} \longleftrightarrow C = \{\#\}$
unfolding *atms-of-def image-def Collect-empty-eq*
by (*metis all-not-in-conv set-mset-eq-empty-iff*)

lemma
 $\text{atms-of-poss[simp]}$: $\text{atms-of } (\text{poss } AA) = \text{set-mset } AA$ **and**
 $\text{atms-of-negg[simp]}$: $\text{atms-of } (\text{negs } AA) = \text{set-mset } AA$
unfolding *atms-of-def image-def* **by** *auto*

lemma *less-eq-Max-atms-of*: $C \neq \{\#\} \implies C \# \subseteq \# D \implies \text{Max } (\text{atms-of } C) \leq \text{Max } (\text{atms-of } D)$
unfolding *atms-of-def*
by (*metis Max-atm-of-set-mset-commute le-multiset-empty-right leq-imp-less-eq-atm-of less-eq-Max-lit*)

lemma *le-multiset-Max-in-imp-Max*:
 $\text{Max } (\text{atms-of } D) = A \implies C \# \subseteq \# D \implies A \in \text{atms-of } C \implies \text{Max } (\text{atms-of } C) = A$

by (*metis* *Max.coboundedI*[*OF finite-atms-of*] *atms-of-def empty-iff eq-iff image-subsetI*
less-eq-Max-atms-of set-mset-empty subset-Compl-self-eq)

lemma *atm-of-Max-lit[simp]*: $C \neq \{\#\} \implies \text{atm-of } (\text{Max } (\text{set-mset } C)) = \text{Max } (\text{atms-of } C)$
unfolding *atms-of-def Max-atm-of-set-mset-commute ..*

lemma *Max-lit-eq-pos-or-neg-Max-atm*:

$C \neq \{\#\} \implies \text{Max } (\text{set-mset } C) = \text{Pos } (\text{Max } (\text{atms-of } C)) \vee \text{Max } (\text{set-mset } C) = \text{Neg } (\text{Max } (\text{atms-of } C))$

by (*metis* *Neg-atm-of-iff Pos-atm-of-iff atm-of-Max-lit*)

lemma *atms-less-imp-lit-less-pos*: $(\bigwedge B. B \in \text{atms-of } C \implies B < A) \implies L \in \# C \implies L < \text{Pos } A$
unfolding *atms-of-def less-literal-def* **by** *force*

lemma *atms-less-eq-imp-lit-less-eq-neg*: $(\bigwedge B. B \in \text{atms-of } C \implies B \leq A) \implies L \in \# C \implies L \leq \text{Neg } A$
unfolding *less-eq-literal-def* **by** (*simp add: atm-of-lit-in-atms-of*)

end

2.2 Herbrand Intepretation

theory *Herbrand-Interpretation*

imports *Clausal-Logic*

begin

Resolution operates of clauses, which are disjunctions of literals. The material formalized here corresponds roughly to Sections 2.2 (“Herbrand Interpretations”) of Bachmair and Ganzinger, excluding the formula and term syntax.

2.2.1 Herbrand Interpretations

A Herbrand interpretation is a set of ground atoms that are to be considered true.

type-synonym *'a interp* = *'a set*

definition *true-lit* :: *'a interp* \Rightarrow *'a literal* \Rightarrow *bool* (**infix** \models_l 50) **where**
 $I \models_l L \longleftrightarrow (\text{if is-pos } L \text{ then } (\lambda P. P) \text{ else Not } (\text{atm-of } L \in I))$

lemma *true-lit-simps[simp]*:

$I \models_l \text{Pos } A \longleftrightarrow A \in I$

$I \models_l \text{Neg } A \longleftrightarrow A \notin I$

unfolding *true-lit-def* **by** *auto*

lemma *true-lit-iff[iff]*: $I \models_l L \longleftrightarrow (\exists A. L = \text{Pos } A \wedge A \in I \vee L = \text{Neg } A \wedge A \notin I)$
by (*cases L*) *simp+*

definition *true-cls* :: *'a interp* \Rightarrow *'a clause* \Rightarrow *bool* (**infix** \models 50) **where**
 $I \models C \longleftrightarrow (\exists L. L \in \# C \wedge I \models_l L)$

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

unfolding *true-cls-def* **by** *simp*

lemma *true-cls-singleton[iff]*: $I \models \{\#L\# \} \longleftrightarrow I \models_l L$

unfolding *true-cls-def* **by** *simp*

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*: $\text{set-mset } C \subseteq \text{set-mset } D \implies I \models C \implies I \models D$
unfolding *true-cls-def* *subset-eq* **by** *metis*

lemma
assumes $I \subseteq J$
shows
false-to-true-imp-ex-pos: $\neg I \models C \implies J \models C \implies \exists A \in J. \text{Pos } A \in \# C$ **and**
true-to-false-imp-ex-neg: $I \models C \implies \neg J \models C \implies \exists A \in J. \text{Neg } A \in \# C$
using *assms* **unfolding** *subset-iff* *true-cls-def*
by (*metis literal.collapse true-lit-simps*)+

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 *pos-literal-in-imp-true-cls*[*intro*]: $\text{Pos } A \in \# C \implies A \in I \implies I \models C$
by (*metis true-cls-def true-lit-simps*(1))

lemma *neg-literal-notin-imp-true-cls*[*intro*]: $\text{Neg } A \in \# C \implies A \notin I \implies I \models C$
by (*metis true-cls-def true-lit-simps*(2))

lemma *pos-neg-in-imp-true*: $\text{Pos } A \in \# C \implies \text{Neg } A \in \# C \implies I \models C$
unfolding *true-cls-def* **by** (*metis true-lit-simps*)

definition *true-clss* :: 'a *interp* \Rightarrow 'a *clause set* \Rightarrow *bool* (**infix** \models_s 50) **where**
 $I \models_s CC \longleftrightarrow (\forall C \in CC. I \models C)$

lemma *true-clss-empty*[*iff*]: $I \models_s \{\}$
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-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-mono*: $DD \subseteq CC \implies I \models_s CC \implies I \models_s DD$
unfolding *true-clss-def* **by** *blast*

abbreviation *satisfiable* :: 'a *clause set* \Rightarrow *bool* **where**
satisfiable $CC \equiv \exists I. I \models_s CC$

definition *true-cls-mset* :: 'a *interp* \Rightarrow 'a *clause multiset* \Rightarrow *bool* (**infix** \models_m 50) **where**
 $I \models_m CC \longleftrightarrow (\forall C. C \in \# CC \longrightarrow I \models C)$

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

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

lemma *true-cls-mset-union*[*iff*]: $I \models_m CC + DD \longleftrightarrow I \models_m CC \wedge I \models_m DD$
unfolding *true-cls-mset-def* **by** *auto*

lemma *true-cls-mset-image-mset*[*iff*]: $I \models_m \text{image-mset } f \ A \longleftrightarrow (\forall x . x \in \# \ A \longrightarrow I \models f \ x)$
unfolding *true-cls-mset-def* **by** *auto*

lemma *true-cls-mset-mono*: $\text{set-mset } DD \subseteq \text{set-mset } CC \implies I \models_m CC \implies I \models_m DD$
unfolding *true-cls-mset-def subset-iff* **by** *auto*

lemma *true-clss-set-mset*[*iff*]: $I \models_s \text{set-mset } CC \longleftrightarrow I \models_m CC$
unfolding *true-clss-def true-cls-mset-def* **by** *auto*

end

2.3 Partial Clausal Logic

theory *Partial-Clausal-Logic*
imports *../lib/Clausal-Logic List-More*
begin

We define here entailment by a set of literals. This is *not* an Herbrand interpretation and has different properties. One key difference is that such a set can be inconsistent (i.e. containing both L and $-L$).

Satisfiability is defined by the existence of a total and consistent model.

2.3.1 Clauses

Clauses are (finite) multisets of literals.

type-synonym *'a clause* = *'a literal multiset*
type-synonym *'v clauses* = *'v clause set*

2.3.2 Partial Interpretations

type-synonym *'a interp* = *'a literal set*

definition *true-lit* :: *'a interp* \Rightarrow *'a literal* \Rightarrow *bool* (**infix** \models_l 50) **where**
 $I \models_l L \longleftrightarrow L \in I$

declare *true-lit-def*[*simp*]

Consistency

definition *consistent-interp* :: *'a literal set* \Rightarrow *bool* **where**
 $\text{consistent-interp } I = (\forall L. \neg(L \in I \wedge -L \in I))$

lemma *consistent-interp-empty*[*simp*]:
 $\text{consistent-interp } \{\}$ **unfolding** *consistent-interp-def* **by** *auto*

lemma *consistent-interp-single*[*simp*]:
 $\text{consistent-interp } \{L\}$ **unfolding** *consistent-interp-def* **by** *auto*

lemma *consistent-interp-subset*:
assumes
 $A \subseteq B$ **and**
 $\text{consistent-interp } B$
shows $\text{consistent-interp } A$
using *assms* **unfolding** *consistent-interp-def* **by** *auto*

lemma *consistent-interp-change-insert*:

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

lemma *consistent-interp-insert-pos[simp]*:

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

lemma *consistent-interp-insert-not-in*:

$\text{consistent-interp } A \implies a \notin A \implies -a \notin A \implies \text{consistent-interp } (\text{insert } a A)$
unfolding *consistent-interp-def* **by** *auto*

Atoms

We define here various lifting of *atm-of* (applied to a single literal) to set and multisets of literals.

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-mmltiset[simp]*:

$\text{atms-of } (\text{mset } a) = \text{atm-of } ' \text{ set } a$
by (*induct a*) *auto*

lemma *atms-of-ms-mset-unfold*:

$\text{atms-of-ms } (\text{mset } ' b) = (\bigcup x \in b. \text{atm-of } ' \text{ set } x)$
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]*:

$\text{atms-of-ms } \{\} = \{\}$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-mempty[simp]*:

$\text{atms-of-ms } \{\{\#\}\} = \{\}$
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]*: *atms-of-ms* $\{L\} = \text{atms-of } L$
unfolding *atms-of-ms-def* **by** *auto*

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

lemma *atms-of-ms-single-set-mset-atms-of[simp]*:
 $\text{atms-of-ms } (\text{single } ' \text{ set-mset } B) = \text{atms-of } B$
unfolding *atms-of-ms-def atms-of-def* **by** *auto*

lemma *atms-of-ms-remove-incl*:
shows $\text{atms-of-ms } (\text{Set.remove } a \ \psi) \subseteq \text{atms-of-ms } \psi$
unfolding *atms-of-ms-def* **by** *auto*

lemma *atms-of-ms-remove-subset*:
 $\text{atms-of-ms } (\varphi - \psi) \subseteq \text{atms-of-ms } \varphi$
unfolding *atms-of-ms-def* **by** *auto*

lemma *finite-atms-of-ms-remove-subset[simp]*:
 $\text{finite } (\text{atms-of-ms } A) \implies \text{finite } (\text{atms-of-ms } (A - C))$
using *atms-of-ms-remove-subset[of A C] finite-subset* **by** *blast*

lemma *atms-of-ms-empty-iff*:
 $\text{atms-of-ms } A = \{\} \longleftrightarrow A = \{\{\#\}\} \vee A = \{\}$
apply (*rule iffI*)
apply (*metis (no-types, lifting) atms-empty-iff-empty atms-of-atms-of-ms-mono insert-absorb singleton-iff singleton-insert-inj-eq' subsetI subset-empty*)
apply *auto*[]
done

lemma *in-implies-atm-of-on-atms-of-ms*:
assumes $L \in \# \ C$ **and** $C \in N$
shows $\text{atm-of } L \in \text{atms-of-ms } N$
using *atms-of-atms-of-ms-mono[of C N] assms* **by** (*simp add: atm-of-lit-in-atms-of subset-iff*)

lemma *in-plus-implies-atm-of-on-atms-of-ms*:
assumes $C + \{\#L\} \in N$
shows $\text{atm-of } L \in \text{atms-of-ms } N$
using *in-implies-atm-of-on-atms-of-ms[of - C + {\#L\}] assms* **by** *auto*

lemma *in-m-in-literals*:
assumes $\{\#A\} + D \in \psi$
shows $\text{atm-of } A \in \text{atms-of-ms } \psi$
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]*:
 $\text{atms-of-s } (\text{insert } L \ Ib) = \{\text{atm-of } L\} \cup \text{atms-of-s } Ib$

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+*

Totality

definition *total-over-set* :: *'a interp* \Rightarrow *'a set* \Rightarrow *bool* **where**

total-over-set I S = $(\forall l \in S. \text{Pos } l \in I \vee \text{Neg } l \in I)$

definition *total-over-m* :: *'a literal set* \Rightarrow *'a clause set* \Rightarrow *bool* **where**

total-over-m I ψ s = *total-over-set I* (*atms-of-ms ψ s*)

lemma *total-over-set-empty*[*simp*]:

total-over-set I {}

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

lemma *total-over-m-empty*[*simp*]:

total-over-m I {}

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

lemma *total-over-set-single*[*iff*]:

$\text{total-over-set } I \{L\} \longleftrightarrow (\text{Pos } L \in I \vee \text{Neg } L \in I)$

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

lemma *total-over-set-insert*[*iff*]:

$\text{total-over-set } I (\text{insert } L \text{ } Ls) \longleftrightarrow ((\text{Pos } L \in I \vee \text{Neg } L \in I) \wedge \text{total-over-set } I Ls)$

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

lemma *total-over-set-union*[*iff*]:

$\text{total-over-set } I (Ls \cup Ls') \longleftrightarrow (\text{total-over-set } I Ls \wedge \text{total-over-set } I Ls')$

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

lemma *total-over-m-subset*:

$A \subseteq B \implies \text{total-over-m } I B \implies \text{total-over-m } I A$

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 $\text{total-over-m } I \{C + D\} \longleftrightarrow (\text{total-over-m } I \{C\} \wedge \text{total-over-m } I \{D\})$

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

lemma *total-over-m-union*[*iff*]:

$\text{total-over-m } I (A \cup B) \longleftrightarrow (\text{total-over-m } I A \wedge \text{total-over-m } I B)$

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-m*[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 ψs)*
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}) { ψ }*
and $L: L \notin \# \psi \ -L \notin \# \psi$
shows *total-over-m I { ψ }*
unfolding *total-over-m-def total-over-set-def*

proof

fix l
assume $l: l \in atms-of-ms\ \{\psi\}$
then have $Pos\ l \in I \vee Neg\ l \in I \vee l = atm-of\ L$
using *assms unfolding total-over-m-def total-over-set-def* **by** *auto*
moreover have $atm-of\ L \notin atms-of-ms\ \{\psi\}$

```

proof (rule ccontr)
  assume  $\neg$  ?thesis
  then have  $\text{atm-of } L \in \text{atms-of } \psi$  by auto
  then have  $\text{Pos } (\text{atm-of } L) \in\# \psi \vee \text{Neg } (\text{atm-of } L) \in\# \psi$ 
    using atm-imp-pos-or-neg-lit by metis
  then have  $L \in\# \psi \vee \neg L \in\# \psi$  by (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

```

Interpretations

definition true-cls :: 'a interp \Rightarrow 'a clause \Rightarrow bool (infix \models 50) **where**
 $I \models C \longleftrightarrow (\exists L \in\# C. I \models_l L)$

```

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

```

```

lemma true-cls-singleton[iff]:  $I \models \{\#L\# \} \longleftrightarrow I \models_l L$ 
  unfolding true-cls-def by (auto split:if-split-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: set-mset C  $\subseteq$  set-mset D  $\Longrightarrow I \models C \Longrightarrow I \models D$ 
  unfolding true-cls-def subset-eq Bex-def by metis

```

```

lemma true-cls-mono-leD[dest]: A  $\subseteq\# B \Longrightarrow I \models A \Longrightarrow I \models B$ 
  unfolding true-cls-def by auto

```

```

lemma
  assumes I  $\models \psi$ 
  shows
    true-cls-union-increase[simp]: I  $\cup$  I'  $\models \psi$  and
    true-cls-union-increase'[simp]: I'  $\cup$  I  $\models \psi$ 
  using assms unfolding true-cls-def by auto

```

```

lemma true-cls-mono-set-mset-l:
  assumes A  $\models \psi$ 
  and A  $\subseteq B$ 
  shows B  $\models \psi$ 
  using assms unfolding true-cls-def by auto

```

```

lemma true-cls-replicate-mset[iff]: I  $\models \text{replicate-mset } n \ L \longleftrightarrow n \neq 0 \wedge I \models_l L$ 

```

by (induct n) auto

lemma *true-cls-empty-entails*[iff]: $\neg \{\} \models N$
 by (auto simp add: true-cls-def)

lemma *true-cls-not-in-remove*:
 assumes $L \notin \# \chi$ and $I \cup \{L\} \models \chi$
 shows $I \models \chi$
 using *assms* **unfolding** *true-cls-def* **by** *auto*

definition *true-clss* :: '*a* interp \Rightarrow '*a* clauses \Rightarrow bool (infix \models_s 50) **where**
 $I \models_s CC \longleftrightarrow (\forall C \in CC. I \models C)$

lemma *true-clss-empty*[simp]: $I \models_s \{\}$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-singleton*[iff]: $I \models_s \{C\} \longleftrightarrow I \models C$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-empty-entails-empty*[iff]: $\{\} \models_s N \longleftrightarrow N = \{\}$
unfolding *true-clss-def* **by** (auto simp add: true-cls-def)

lemma *true-cls-insert-l* [simp]:
 $M \models A \implies \text{insert } L \ M \models A$
unfolding *true-cls-def* **by** *auto*

lemma *true-clss-union*[iff]: $I \models_s CC \cup DD \longleftrightarrow I \models_s CC \wedge I \models_s DD$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-insert*[iff]: $I \models_s \text{insert } C \ DD \longleftrightarrow I \models C \wedge I \models_s DD$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-mono*: $DD \subseteq CC \implies I \models_s CC \implies I \models_s DD$
unfolding *true-clss-def* **by** *blast*

lemma *true-clss-union-increase*[simp]:
 assumes $I \models_s \psi$
 shows $I \cup I' \models_s \psi$
 using *assms* **unfolding** *true-clss-def* **by** *auto*

lemma *true-clss-union-increase'*[simp]:
 assumes $I' \models_s \psi$
 shows $I \cup I' \models_s \psi$
 using *assms* **by** (auto simp add: true-clss-def)

lemma *true-clss-commute-l*:
 $(I \cup I' \models_s \psi) \longleftrightarrow (I' \cup I \models_s \psi)$
by (simp add: Un-commute)

lemma *model-remove*[simp]: $I \models_s N \implies I \models_s \text{Set.remove } a \ N$
by (simp add: true-clss-def)

lemma *model-remove-minus*[simp]: $I \models_s N \implies I \models_s N - A$
by (simp add: true-clss-def)

lemma *notin-vars-union-true-cls-true-cls*:

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-cls-def true-lit-def Bex-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-cls-true-cls subset-trans*)

Satisfiability

definition *satisfiable* :: 'a clause set \Rightarrow bool **where**
satisfiable $CC \equiv \exists I. (I \models_s CC \wedge \text{consistent-interp } I \wedge \text{total-over-m } I \text{ } CC)$

lemma *satisfiable-single[simp]*:
satisfiable $\{\{\#L\#\}\}$
unfolding *satisfiable-def* **by** *fastforce*

abbreviation *unsatisfiable* :: 'a clause set \Rightarrow bool **where**
unsatisfiable $CC \equiv \neg \text{satisfiable } CC$

lemma *satisfiable-decreasing*:
assumes *satisfiable* $(\psi \cup \psi')$
shows *satisfiable* ψ
using *assms total-over-m-union unfolding satisfiable-def* **by** *blast*

lemma *satisfiable-def-min*:
satisfiable CC
 $\longleftrightarrow (\exists I. I \models_s CC \wedge \text{consistent-interp } I \wedge \text{total-over-m } I \text{ } CC \wedge \text{atm-of } I = \text{atms-of-ms } CC)$
(is ?sat \longleftrightarrow ?B)

proof

assume $?B$ **then show** $?sat$ **by** (*auto simp add: satisfiable-def*)

next

assume $?sat$

then obtain I **where**

I-CC: $I \models_s CC$ **and**

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

tot: *total-over-m* $I \text{ } CC$

unfolding *satisfiable-def* **by** *auto*

let $?I = \{P. P \in I \wedge \text{atm-of } P \in \text{atms-of-ms } CC\}$

have *I-CC*: $?I \models_s CC$

using *I-CC in-implies-atm-of-on-atms-of-ms unfolding true-clss-def Ball-def true-cls-def Bex-def true-lit-def*
by *blast*

moreover have *cons*: *consistent-interp* $?I$

using *cons unfolding consistent-interp-def* **by** *auto*

moreover have *total-over-m* $?I \text{ } CC$

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

moreover
 have *atms-CC-incl*: *atms-of-ms CC* \subseteq *atm-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-of ' ?I = atms-of-ms CC*
 using *atms-CC-incl unfolding atms-of-ms-def by force*
 ultimately show *?B* by *auto*
qed

lemma *satisfiable-carac[iff]*:
 $(\exists I. \text{consistent-interp } I \wedge I \models_s \varphi) \longleftrightarrow \text{satisfiable } \varphi$ (is $(\exists I. ?Q I) \longleftrightarrow ?S$)
proof
 assume *?S*
 then show $\exists I. ?Q I$ **unfolding** *satisfiable-def* by *auto*
next
 assume $\exists I. ?Q I$
 then obtain *I* where *cons*: *consistent-interp I* and *I*: $I \models_s \varphi$ by *metis*
 let *?I'* = $\{Pos\ v \mid v. v \notin \text{atms-of-s } I \wedge v \in \text{atms-of-ms } \varphi\}$
 have *consistent-interp* ($I \cup ?I'$)
 using *cons unfolding consistent-interp-def* by (*intro allI*) (*rename-tac L, case-tac L, auto*)
 moreover have *total-over-m* ($I \cup ?I'$) φ
 unfolding *total-over-m-def total-over-set-def* by *auto*
 moreover have $I \cup ?I' \models_s \varphi$
 using *I unfolding Ball-def true-clss-def true-cls-def* by *auto*
 ultimately show *?S* **unfolding** *satisfiable-def* by *blast*
qed

lemma *satisfiable-carac'[simp]*: *consistent-interp I* $\implies I \models_s \varphi \implies \text{satisfiable } \varphi$
 using *satisfiable-carac* by *metis*

Entailment for Multisets of Clauses

definition *true-cls-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-cls-mset-empty[simp]*: $I \models_m \{\#\}$
 unfolding *true-cls-mset-def* by *auto*

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

lemma *true-cls-mset-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-cls-mset-image-mset[iff]*: $I \models_m \text{image-mset } f\ A \longleftrightarrow (\forall x \in \# A. I \models f\ x)$
 unfolding *true-cls-mset-def* by *fastforce*

lemma *true-cls-mset-mono*: *set-mset DD* \subseteq *set-mset CC* $\implies I \models_m CC \implies I \models_m DD$
 unfolding *true-cls-mset-def subset-iff* by *auto*

lemma *true-clss-set-mset[iff]*: $I \models_s \text{set-mset } CC \longleftrightarrow I \models_m CC$
 unfolding *true-clss-def true-cls-mset-def* by *auto*

lemma *true-cls-mset-increasing-r[simp]*:
 $I \models_m CC \implies I \cup J \models_m CC$
 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  $\psi$ 
  shows total-over-m  $\{v \in I. \text{atm-of } v \in \text{atms-of-ms } \psi\}$   $\psi$ 
  using assms unfolding total-over-m-def total-over-set-def
  by (metis (lifting) literal.sel(1,2) mem-Collect-eq)

```

```

lemma true-cls-remove-hd-if-notin-vars:
  assumes insert a  $M' \models D$ 
  and atm-of a  $\notin \text{atms-of } D$ 
  shows  $M' \models D$ 
  using assms by (auto simp add: atm-of-lit-in-atms-of true-cls-def)

```

```

lemma total-over-set-atm-of:
  fixes I :: 'v interp and K :: 'v set
  shows total-over-set I K  $\longleftrightarrow (\forall l \in K. l \in (\text{atm-of } I))$ 
  unfolding total-over-set-def by (metis atms-of-s-def in-atms-of-s-decomp)

```

Tautologies

We define tautologies as clauses entailed by every total model and show later that is equivalent to containing a literal and its negation.

definition *tautology* ($\psi :: 'v \text{ clause}$) $\equiv \forall I. \text{total-over-set } I (\text{atms-of } \psi) \longrightarrow I \models \psi$

```

lemma tautology-Pos-Neg[intro]:
  assumes Pos p  $\in\# A$  and Neg p  $\in\# A$ 
  shows tautology A
  using assms unfolding tautology-def total-over-set-def true-cls-def Bex-def
  by (meson atm-iff-pos-or-neg-lit true-lit-def)

```

```

lemma tautology-minus[simp]:
  assumes L  $\in\# A$  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  $\psi$ 
  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  $\psi$ )
    unfolding total-over-set-def using atm-imp-pos-or-neg-lit by force
  moreover have  $\neg ?I \models \psi$ 
    unfolding true-cls-def true-lit-def Bex-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:

```


$\text{tautology } \psi \longleftrightarrow (\exists p. \text{Pos } p \in \# \psi \wedge \text{Neg } p \in \# \psi)$
using *tautology-exists-Pos-Neg* **by** *auto*

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

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

lemma *minus-interp-tautology:*
assumes $\{-L \mid L. L \in \# \chi\} \models \chi$
shows *tautology* χ
proof –
obtain L **where** $L \in \# \chi \wedge -L \in \# \chi$
using *assms* **unfolding** *true-cls-def* **by** *auto*
then show *?thesis* **using** *tautology-decomp literal.exhaust uminus-Neg uminus-Pos* **by** *metis*
qed

lemma *remove-literal-in-model-tautology:*
assumes $I \cup \{\text{Pos } P\} \models \varphi$
and $I \cup \{\text{Neg } P\} \models \varphi$
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* χ
shows *tautology* χ' **unfolding** *tautology-def*
proof (*intro allI HOL.impI*)
fix $I :: 'v \text{ literal set}$
assume *totI: total-over-set* I (*atms-of* χ')
let $?I' = \{\text{Pos } v \mid v. v \in \text{atms-of } \chi \wedge v \notin \text{atms-of-s } I\}$
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 $\bigwedge L. L \in \# \chi' \implies L \notin ?I'$
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

Entailment for clauses and propositions

We also need entailment of clauses by other clauses.

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-clss-in[simp]:
   $CC \in A \implies A \models_p CC$ 
  unfolding true-clss-clss-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
         $\text{tot}AC: \text{total-over-m } I \ (A \cup C) \ \text{and}$ 
         $\text{cons}: \text{consistent-interp } I \ \text{and}$ 
         $I: I \models_s A$ 
      then have  $\text{tot}: \text{total-over-m } I \ A \ \text{and } \text{tot}': \text{total-over-m } I \ C \ \text{by } \text{auto}$ 
      obtain  $I'$  where
         $\text{tot}': \text{total-over-m } (I \cup I') \ (A \cup C \cup D) \ \text{and}$ 
         $\text{cons}': \text{consistent-interp } (I \cup I') \ \text{and}$ 
         $H: \forall x \in I'. \text{atm-of } x \in \text{atms-of-ms } D \wedge \text{atm-of } x \notin \text{atms-of-ms } (A \cup C)$ 
        using total-over-m-consistent-extension[OF - cons, of A C] tot tot' by blast
      moreover have  $I \cup I' \models_s A \ \text{using } I \ \text{by } \text{simp}$ 
      ultimately have  $I \cup I' \models_s C \cup D \ \text{using } A \ \text{unfolding } \text{true-clss-clss-def} \ \text{by } \text{auto}$ 
      then have  $I \cup I' \models_s C \cup D \ \text{by } \text{auto}$ 
      then show  $I \models_s C \ \text{using } \text{notin-vars-union-true-clss-true-clss}[of I'] \ H \ \text{by } \text{auto}$ 
    qed
  } note  $H = \text{this}$ 
  assume  $A \models_{ps} C \cup D$ 
  then show  $A \models_{ps} C \wedge A \models_{ps} D \ \text{using } H[of A] \ \text{Un-commute}[of C D] \ \text{by } \text{metis}$ 
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 $B \models_{ps} C$
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  $L \text{ tot}$  by (cases  $L$ ) auto
  then have  $I \models C + \{\#L\#\}$ 
    using  $C \langle I \models N \rangle \text{ tot} \langle \text{consistent-interp } I \rangle$  unfolding true-clss-cls-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  $?I' \models N$  using  $\langle I \models N \rangle$  using true-clss-union-increase by blast
  ultimately have  $?I' \models D + \{\#- L\#\}$ 
    using  $D$  unfolding true-clss-cls-def by blast
  then have  $?I' \models D$  using  $L$  by auto
  moreover
    have total-over-set  $I$  (atms-of  $(D + C)$ ) using tot by auto
    then have  $L \notin \# D \wedge -L \notin \# D$ 
      using  $L$  unfolding total-over-set-def atms-of-def by (cases  $L$ ) force+
    ultimately have  $I \models D + C$  unfolding true-cls-def by auto
  }
  ultimately show  $I \models D + C$  by blast
qed

```

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

lemma *true-clss-clss-union-mset-true-clss-clss-or-not-true-clss-clss-or*:

```

assumes
   $D: N \models_p D + \{\#- L\#\}$  and
   $C: N \models_p C + \{\#L\#\}$ 
shows  $N \models_p D \# \cup C$ 
unfolding true-clss-clss-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  $D \langle I \models_s N \rangle \text{ tot} \langle \text{consistent-interp } I \rangle$  unfolding true-clss-clss-def by auto
    moreover
      have total-over-m  $I \{C + \{\#L\#\}\}$ 
        using  $L \text{ tot}$  by (cases  $L$ ) auto
      then have  $I \models C + \{\#L\#\}$ 
        using  $C \langle I \models_s N \rangle \text{ tot} \langle \text{consistent-interp } I \rangle$  unfolding true-clss-clss-def by auto
      ultimately have  $I \models D \# \cup C$  using  $\langle \text{consistent-interp } I \rangle$  unfolding consistent-interp-def
        by auto
    }
  }

```

```

moreover {
  assume  $L: L \notin I \wedge -L \notin I$ 
  let  $?I' = I \cup \{L\}$ 
  have consistent-interp  $?I'$  using  $L \langle \text{consistent-interp } I \rangle$  by auto
  moreover have total-over-m  $?I' \{D + \{\#- L\#\}\}$ 
    using tot unfolding total-over-m-def total-over-set-def by (auto simp add: atms-of-def)
  moreover have total-over-m  $?I' N$  using tot using total-union by blast
  moreover have  $?I' \models_s N$  using  $\langle I \models_s N \rangle$  using true-clss-union-increase by blast
  ultimately have  $?I' \models D + \{\#- L\#\}$ 
    using  $D$  unfolding true-clss-cls-def by blast
  then have  $?I' \models D$  using  $L$  by auto
  moreover
    have total-over-set  $I$  (atms-of  $(D + C)$ ) using tot by auto
    then have  $L \notin \# D \wedge -L \notin \# D$ 
      using  $L$  unfolding total-over-set-def atms-of-def by (cases L) force+
    ultimately have  $I \models D \# \cup C$  unfolding true-cls-def by auto
  }
  ultimately show  $I \models D \# \cup C$  by blast
qed

```

2.3.3 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 (fastforce simp: atm-of-eq-atm-of atms-of-def)

```

lemma *subsumption-chained*:

```

assumes
   $\forall I. \text{total-over-m } I \{D\} \longrightarrow I \models D \longrightarrow I \models \varphi$  and
   $C \subseteq \# D$ 
shows  $(\forall I. \text{total-over-m } I \{C\} \longrightarrow I \models C \longrightarrow I \models \varphi) \vee \text{tautology } \varphi$ 
using assms

```

proof (*induct card* $\{Pos \ v \mid v. v \in \text{atms-of } D \wedge v \notin \text{atms-of } C\}$ *arbitrary*: D
rule: nat-less-induct-case)

```

case 0 note  $n = \text{this}(1)$  and  $H = \text{this}(2)$  and  $\text{incl} = \text{this}(3)$ 
then have atms-of  $D \subseteq \text{atms-of } C$  by auto
then have  $\forall I. \text{total-over-m } I \{C\} \longrightarrow \text{total-over-m } I \{D\}$ 
  unfolding total-over-m-def total-over-set-def by auto
moreover have  $\forall I. I \models C \longrightarrow I \models D$  using incl true-cls-mono-leD by blast
ultimately show  $?case$  using  $H$  by auto

```

next

```

case (Suc  $n \ D$ ) note  $IH = \text{this}(1)$  and  $\text{card} = \text{this}(2)$  and  $H = \text{this}(3)$  and  $\text{incl} = \text{this}(4)$ 
let  $?atms = \{Pos \ v \mid v. v \in \text{atms-of } D \wedge v \notin \text{atms-of } C\}$ 
have finite  $?atms$  by auto
then obtain  $L$  where  $L: L \in ?atms$ 
  using card by (metis (no-types, lifting) Collect-empty-eq card-0-eq mem-Collect-eq  

nat.simps(3))
let  $?D' = D - \text{replicate-mset } (\text{count } D \ L) \ L - \text{replicate-mset } (\text{count } D \ (-L)) \ (-L)$ 
have atms-of-D: atms-of-ms  $\{D\} \subseteq \text{atms-of-ms } \{?D'\} \cup \{\text{atm-of } L\}$  by auto

```

```

{
  fix I
  assume total-over-m I {?D'}
  then have tot: total-over-m (I ∪ {L}) {D}
    unfolding total-over-m-def total-over-set-def using atms-of-D by auto

  assume IDL: I ⊨ ?D'
  then have I ∪ {L} ⊨ D unfolding true-cls-def by force
  then have I ∪ {L} ⊨ φ using H tot by auto

  moreover
    have tot': total-over-m (I ∪ {-L}) {D}
      using tot unfolding total-over-m-def total-over-set-def by auto
    have I ∪ {-L} ⊨ D using IDL unfolding true-cls-def by force
    then have I ∪ {-L} ⊨ φ using H tot' by auto
  ultimately have I ⊨ φ ∨ tautology φ
    using L remove-literal-in-model-tautology by force
} note H' = this

have L ∉# C and -L ∉# C using L atm-iff-pos-or-neg-lit by force+
then have C-in-D': C ⊆# ?D' using ⟨C ⊆# D⟩ by (auto simp: subseq-mset-def not-in-iff)
have card {Pos v | v. v ∈ atms-of ?D' ∧ v ∉ atms-of C} <
  card {Pos v | v. v ∈ atms-of D ∧ v ∉ atms-of C}
  using L by (auto intro!: psubset-card-mono)
then show ?case
  using IH C-in-D' H' unfolding card[symmetric] by blast
qed

```

2.3.4 Removing Duplicates

```

lemma tautology-remdups-mset[iff]:
  tautology (remdups-mset C) ⟷ tautology C
  unfolding tautology-decomp by auto

lemma atms-of-remdups-mset[simp]: atms-of (remdups-mset C) = atms-of C
  unfolding atms-of-def by auto

lemma true-cls-remdups-mset[iff]: I ⊨ remdups-mset C ⟷ I ⊨ C
  unfolding true-cls-def by auto

lemma true-clss-cls-remdups-mset[iff]: A ⊨p remdups-mset C ⟷ A ⊨p C
  unfolding true-clss-cls-def total-over-m-def by auto

```

2.3.5 Set of all Simple Clauses

A simple clause with respect to a set of atoms is such that

1. its atoms are included in the considered set of atoms;
2. it is not a tautology;
3. it does not contains duplicate literals.

It corresponds to the clauses that cannot be simplified away in a calculus without considering the other 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*) =
 $(\text{op} + \{\#\text{Pos } l\}) \text{ ' } (\text{simple-clss } \text{atms})$
 $\cup (\text{op} + \{\#\text{Neg } l\}) \text{ ' } (\text{simple-clss } \text{atms})$
 $\cup \text{simple-clss } \text{atms}(\text{is } ?I = ?U)$

proof (*standard*; *standard*)

fix C

assume $C \in ?I$

then have

atms: $\text{atms-of } C \subseteq \text{insert } l \text{ atms}$ **and**

taut: $\neg \text{tautology } C$ **and**

dist: *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

(*Add*) $L \text{ where } L \in \# C \text{ and } L = \text{Neg } l \vee L = \text{Pos } l$

| (*No*) $\text{Pos } l \notin \# C \text{ Neg } l \notin \# C$

by *auto*

then show $C \in ?U$

proof *cases*

case *Add*

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

using *dist* **unfolding** *distinct-mset-def* **by** (*auto simp: not-in-iff*)

have $LC: -L \notin \# C$

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

obtain $aa :: 'a$ **where**

$f4: (aa \in \text{atms-of } (\text{remove1-mset } L C) \longrightarrow aa \in \text{atms}) \longrightarrow \text{atms-of } (\text{remove1-mset } L C) \subseteq \text{atms}$
by (*meson subset-iff*)

obtain $ll :: 'a$ *literal* **where**

$aa \notin \text{atm-of ' set-mset } (\text{remove1-mset } L C) \vee aa = \text{atm-of } ll \wedge ll \in \# \text{remove1-mset } L C$
by *blast*

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

using $f4$ *Add LCL LC H* **unfolding** *atms-of-def* **by** (*metis H in-diffD insertE literal.exhaust-sel uminus-Neg uminus-Pos*)

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

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

moreover have *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: if-split-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:
     $\bigwedge C'. \{\#Pos\ l\#\} + C' \notin \text{simple-clss } C$ 
     $\bigwedge C'. \{\#Neg\ l\#\} + C' \notin \text{simple-clss } C$ 
    using l unfolding simple-clss-def by auto
  have H:  $\bigwedge C' D. \{\#Pos\ l\#\} + C' = \{\#Neg\ l\#\} + D \implies D \in \text{simple-clss } C \implies \text{False}$ 
  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 atms  $\subseteq$  simple-clss 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)

```

2.3.6 Experiment: Expressing the Entailments as Locales

```

locale entail =
  fixes entail :: 'a set  $\Rightarrow$  'b  $\Rightarrow$  bool (infix  $\models_e$  50)
  assumes entail-insert[simp]:  $I \neq \{\} \implies \text{insert } L \ I \models_e x \longleftrightarrow \{L\} \models_e x \vee I \models_e x$ 
  assumes entail-union[simp]:  $I \models_e A \implies I \cup I' \models_e A$ 
begin

definition entails :: 'a set  $\Rightarrow$  'b set  $\Rightarrow$  bool (infix  $\models_{es}$  50) where
   $I \models_{es} A \longleftrightarrow (\forall a \in A. I \models_e a)$ 

lemma entails-empty[simp]:
   $I \models_{es} \{\}$ 
  unfolding entails-def by auto

lemma entails-single[iff]:
   $I \models_{es} \{a\} \longleftrightarrow I \models_e a$ 
  unfolding entails-def by auto

lemma entails-insert-l[simp]:
   $M \models_{es} A \implies \text{insert } L \ M \models_{es} A$ 
  unfolding entails-def by (metis Un-commute entail-union insert-is-Un)

lemma entails-union[iff]:  $I \models_{es} CC \cup DD \longleftrightarrow I \models_{es} CC \wedge I \models_{es} DD$ 
  unfolding entails-def by blast

lemma entails-insert[iff]:  $I \models_{es} \text{insert } C \ DD \longleftrightarrow I \models_e C \wedge I \models_{es} DD$ 
  unfolding entails-def by blast

lemma entails-insert-mono:  $DD \subseteq CC \implies I \models_{es} CC \implies I \models_{es} DD$ 
  unfolding entails-def by blast

lemma entails-union-increase[simp]:
  assumes  $I \models_{es} \psi$ 
  shows  $I \cup I' \models_{es} \psi$ 
  using assms unfolding entails-def by auto

lemma true-clss-commute-l:
   $I \cup I' \models_{es} \psi \longleftrightarrow I' \cup I \models_{es} \psi$ 
  by (simp add: Un-commute)

lemma entails-remove[simp]:  $I \models_{es} N \implies I \models_{es} \text{Set.remove } a \ N$ 
  by (simp add: entails-def)

lemma entails-remove-minus[simp]:  $I \models_{es} N \implies I \models_{es} N - A$ 
  by (simp add: entails-def)

end

interpretation true-cl: entail true-cl
  by standard (auto simp add: true-cl-def)

```

2.3.7 Entailment to be extended

In some cases we want a more general version of entailment to have for example $\{\} \models \{\#L, -L\# \}$. This is useful when the model we are building might not be total (the literal L might

have been definitely removed from the set of clauses), but we still want to have a property of entailment considering that theses removed literals are not important.

We can given a model I consider all the natural extensions: C is entailed by an extended I , if for all total extension of I , this model entails C .

definition *true-clss-ext* :: 'a literal set \Rightarrow 'a literal multiset set \Rightarrow bool (**infix** \models_{sext} 49)

where

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

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 $?J = J \cup \{Pos \ (atm\text{-}of \ P) \mid P. P \in \# \ C \wedge atm\text{-}of \ P \notin atm\text{-}of \ 'J\}$

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* \square

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 $\{v \in ?J. atm\text{-}of \ v \in atms\text{-}of\text{-}ms \ (N - \{C\})\} \subseteq J$

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-Logic
imports Main
begin
```


Chapter 3

Normalisation

We define here the normalisation from formula towards conjunctive and disjunctive normal form, including normalisation towards multiset of multisets to represent CNF.

3.1 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.

3.1.1 Definition and abstraction

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

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

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

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

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

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

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

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

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

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

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

```
fun conn :: 'v connective  $\Rightarrow$  'v propo list  $\Rightarrow$  'v propo where
conn CT [] = FT |
conn CF [] = FF |
conn (CVar v) [] = FVar v |
conn CNot [ $\varphi$ ] = FNot  $\varphi$  |
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]:  $(c = CT \vee c = CF \vee c = CVar v) \implies \text{wf-conn } c []$  |
wf-conn-unary[simp]:  $c = CNot \implies \text{wf-conn } c [\psi]$  |
wf-conn-binary[simp]:  $c \in \text{binary-connectives} \implies \text{wf-conn } c (\psi \# \psi' \# [])$ 
thm wf-conn.induct
```

```
lemma wf-conn-induct[consumes 1, case-names CT CF CVar CNot COr CAnd CImp CEq]:
assumes wf-conn c x and
 $\bigwedge v. c = CT \implies P []$  and
 $\bigwedge v. c = CF \implies P []$  and
 $\bigwedge v. c = CVar v \implies P []$  and
 $\bigwedge \psi. c = CNot \implies P [\psi]$  and
 $\bigwedge \psi \psi'. c = COr \implies P [\psi, \psi']$  and
 $\bigwedge \psi \psi'. c = CAnd \implies P [\psi, \psi']$  and
 $\bigwedge \psi \psi'. c = CImp \implies P [\psi, \psi']$  and
 $\bigwedge \psi \psi'. c = CEq \implies P [\psi, \psi']$ 
shows P x
using assms by induction (auto simp: binary-connectives-def)
```

3.1.2 properties of the abstraction

First we can define simplification rules.

```
lemma wf-conn-conn[simp]:
```



```

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

```

```

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

```

```

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

```

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

```

lemma list-length2-decomp: length l = 2  $\implies$  ( $\exists$  a b. l = a # b # [])
apply (induct l, auto)
by (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
  then show wf-conn c l using wf-conn-binary list-length2-decomp using conn by metis
next
  assume wf-conn c l
  then show length l = 2 (is ?P l)
  proof (cases rule: wf-conn.induct)
  case wf-conn-nullary
  then show ?P [] using conn binary-connectives-def
  using connective.distinct(11) connective.distinct(13) connective.distinct(9) by blast
next
  fix ψ :: 'v propo
  case wf-conn-unary
  then show ?P [ψ] using conn binary-connectives-def
  using connective.distinct by blast

```

```

next
  fix  $\psi \psi' :: 'v \text{ propo}$ 
  show  $?P [\psi, \psi']$  by auto
qed
qed

```

```

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

```

Decomposing the Not into an element is moreover very useful.

```

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

```

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

```

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

```

```

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

```

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

```

lemma conn-inj-not:
  assumes  $\text{correct}: \text{wf-conn } c\ l$ 
  and  $\text{conn}: \text{conn } c\ l = FNot\ \psi$ 
  shows  $c = CNot$  and  $l = [\psi]$ 
  apply (cases  $c\ l$  rule: wf-conn.cases)
  using correct conn unfolding binary-connectives-def apply auto
  apply (cases  $c\ l$  rule: wf-conn.cases)
  using correct conn unfolding binary-connectives-def by auto

```

```

lemma conn-inj:
  fixes  $c\ ca :: 'v \text{ connective}$  and  $l\ \psi s :: 'v \text{ propo list}$ 
  assumes  $\text{corr}: \text{wf-conn } ca\ l$ 
  and  $\text{corr}': \text{wf-conn } c\ \psi s$ 

```

```

and eq: conn ca l = conn c  $\psi$ s
shows ca = c  $\wedge$   $\psi$ s = l
using corr
proof (cases ca l rule: wf-conn.cases)
case (wf-conn-nullary v)
then show ca = c  $\wedge$   $\psi$ s = l using assms
by (metis conn.simps(1) conn.simps(2) conn.simps(3) wf-conn-list(1-3))
next
case (wf-conn-unary  $\psi'$ )
then have *: FNot  $\psi'$  = conn c  $\psi$ s using conn-inj-not eq assms by auto
then have c = ca by (metis conn-inj-not(1) corr' wf-conn-unary(2))
moreover have  $\psi$ s = l using * conn-inj-not(2) corr' wf-conn-unary(1) by force
ultimately show ca = c  $\wedge$   $\psi$ s = l by auto
next
case (wf-conn-binary  $\psi'$   $\psi''$ )
then show ca = c  $\wedge$   $\psi$ s = 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

```

3.1.3 Subformulas and properties

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

inductive *subformula* :: '*v* *propo* \Rightarrow '*v* *propo* \Rightarrow bool (infix \preceq 45) for φ where
subformula-refl[simp]: $\varphi \preceq \varphi$ |
subformula-into-subformula: $\psi \in \text{set } l \Rightarrow \text{wf-conn } c \ l \Rightarrow \varphi \preceq \psi \Rightarrow \varphi \preceq \text{conn } c \ l$

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

This is an example of a property related to subformulas.

lemma *subformula-in-subformula-not*:
shows *b*: FNot $\varphi \preceq \psi \Rightarrow \varphi \preceq \psi$
apply (induct rule: subformula.induct)
using *subformula-into-subformula* wf-conn-unary subformula-refl list.set-intros(1) subformula-refl
by (fastforce intro: subformula-into-subformula)+

lemma *subformula-in-binary-conn*:
assumes *conn*: $c \in \text{binary-connectives}$
shows $f \preceq \text{conn } c \ [f, g]$
and $g \preceq \text{conn } c \ [f, g]$
proof –
have *a*: wf-conn $c \ (f \# [g])$ **using** conn wf-conn-binary binary-connectives-def **by** auto
moreover **have** *b*: $f \preceq f$ **using** subformula-refl **by** auto
ultimately **show** $f \preceq \text{conn } c \ [f, g]$
by (metis append-Nil in-set-conv-decomp subformula-into-subformula)
next
have *a*: wf-conn $c \ ([f] @ [g])$ **using** conn wf-conn-binary binary-connectives-def **by** auto
moreover **have** *b*: $g \preceq g$ **using** subformula-refl **by** auto
ultimately **show** $g \preceq \text{conn } c \ [f, g]$ **using** subformula-into-subformula **by** force
qed

lemma *subformula-trans*:

$\psi \preceq \psi' \implies \varphi \preceq \psi \implies \varphi \preceq \psi'$
apply (induct ψ' rule: subformula.inducts)
by (auto simp: subformula-into-subformula)

lemma subformula-leaf:
fixes $\varphi \psi :: 'v \text{ propo}$
assumes incl: $\varphi \preceq \psi$
and simple: $\psi = FT \vee \psi = FF \vee \psi = FVar x$
shows $\varphi = \psi$
using incl simple
by (induct rule: subformula.induct, auto simp: wf-conn-list)

lemma subformula-not-incl-eq:
assumes $\varphi \preceq \text{conn } c \ l$
and wf-conn $c \ l$
and $\forall \psi. \psi \in \text{set } l \longrightarrow \neg \varphi \preceq \psi$
shows $\varphi = \text{conn } c \ l$
using assms **apply** (induction conn $c \ l$ rule: subformula.induct, auto)
using conn-inj **by** blast

lemma wf-subformula-conn-cases:
 $\text{wf-conn } c \ l \implies \varphi \preceq \text{conn } c \ l \longleftrightarrow (\varphi = \text{conn } c \ l \vee (\exists \psi. \psi \in \text{set } l \wedge \varphi \preceq \psi))$
apply standard
using subformula-not-incl-eq **apply** metis
by (auto simp add: subformula-into-subformula)

lemma subformula-decomp-explicit[simp]:
 $\varphi \preceq FAnd \ \psi \ \psi' \longleftrightarrow (\varphi = FAnd \ \psi \ \psi' \vee \varphi \preceq \psi \vee \varphi \preceq \psi')$ (is ?P FAnd)
 $\varphi \preceq FOr \ \psi \ \psi' \longleftrightarrow (\varphi = FOr \ \psi \ \psi' \vee \varphi \preceq \psi \vee \varphi \preceq \psi')$
 $\varphi \preceq FEq \ \psi \ \psi' \longleftrightarrow (\varphi = FEq \ \psi \ \psi' \vee \varphi \preceq \psi \vee \varphi \preceq \psi')$
 $\varphi \preceq FImp \ \psi \ \psi' \longleftrightarrow (\varphi = FImp \ \psi \ \psi' \vee \varphi \preceq \psi \vee \varphi \preceq \psi')$

proof –

have wf-conn CAnd $[\psi, \psi']$ **by** (simp add: binary-connectives-def)
then have $\varphi \preceq \text{conn } CAnd \ [\psi, \psi'] \longleftrightarrow$
 $(\varphi = \text{conn } CAnd \ [\psi, \psi'] \vee (\exists \psi''. \psi'' \in \text{set } [\psi, \psi'] \wedge \varphi \preceq \psi''))$
using wf-subformula-conn-cases **by** metis
then show ?P FAnd **by** auto

next

have wf-conn COr $[\psi, \psi']$ **by** (simp add: binary-connectives-def)
then have $\varphi \preceq \text{conn } COr \ [\psi, \psi'] \longleftrightarrow$
 $(\varphi = \text{conn } COr \ [\psi, \psi'] \vee (\exists \psi''. \psi'' \in \text{set } [\psi, \psi'] \wedge \varphi \preceq \psi''))$
using wf-subformula-conn-cases **by** metis
then show ?P FOr **by** auto

next

have wf-conn CEq $[\psi, \psi']$ **by** (simp add: binary-connectives-def)
then have $\varphi \preceq \text{conn } CEq \ [\psi, \psi'] \longleftrightarrow$
 $(\varphi = \text{conn } CEq \ [\psi, \psi'] \vee (\exists \psi''. \psi'' \in \text{set } [\psi, \psi'] \wedge \varphi \preceq \psi''))$
using wf-subformula-conn-cases **by** metis
then show ?P FEq **by** auto

next

have wf-conn CImp $[\psi, \psi']$ **by** (simp add: binary-connectives-def)
then have $\varphi \preceq \text{conn } CImp \ [\psi, \psi'] \longleftrightarrow$
 $(\varphi = \text{conn } CImp \ [\psi, \psi'] \vee (\exists \psi''. \psi'' \in \text{set } [\psi, \psi'] \wedge \varphi \preceq \psi''))$
using wf-subformula-conn-cases **by** metis
then show ?P FImp **by** auto

qed

```

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

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

lemma subformula-conn-decomp[simp]:
  assumes wf: wf-conn c l
  shows  $\varphi \preceq \text{conn } c l \longleftrightarrow (\varphi = \text{conn } c l \vee (\exists \psi \in \text{set } l. \varphi \preceq \psi))$  (is  $?A \longleftrightarrow ?B$ )
proof (rule iffI)
{
  fix  $\xi$ 
  have  $\varphi \preceq \xi \implies \xi = \text{conn } c l \implies \text{wf-conn } c l \implies \forall x::'a \text{ propo} \in \text{set } l. \neg \varphi \preceq x \implies \varphi = \text{conn } c l$ 
  apply (induct rule: subformula.induct)
  apply simp
  using conn-inj by blast
}
moreover assume  $?A$ 
ultimately show  $?B$  using wf by metis
next
assume  $?B$ 
then show  $\varphi \preceq \text{conn } c l$  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  $\varphi$ ) = vars-of-prop  $\varphi$  |
vars-of-prop (FAnd  $\varphi$   $\psi$ ) = vars-of-prop  $\varphi \cup \text{vars-of-prop } \psi$  |
vars-of-prop (FOr  $\varphi$   $\psi$ ) = vars-of-prop  $\varphi \cup \text{vars-of-prop } \psi$  |
vars-of-prop (FImp  $\varphi$   $\psi$ ) = vars-of-prop  $\varphi \cup \text{vars-of-prop } \psi$  |
vars-of-prop (FEq  $\varphi$   $\psi$ ) = vars-of-prop  $\varphi \cup \text{vars-of-prop } \psi$ 

```

```

lemma vars-of-prop-incl-conn:
  fixes  $\xi \xi' :: 'v \text{ propo list}$  and  $\psi :: 'v \text{ propo}$  and  $c :: 'v \text{ connective}$ 
  assumes corr: wf-conn c l and incl:  $\psi \in \text{set } l$ 
  shows vars-of-prop  $\psi \subseteq \text{vars-of-prop } (\text{conn } c l)$ 
proof (cases c rule: connective-cases-arity-2)

```

```

case nullary
then have False using corr incl by auto
then show vars-of-prop  $\psi \subseteq \text{vars-of-prop } (\text{conn } c \ l)$  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
then have  $\psi = a \vee \psi = b$  using incl by auto
then show vars-of-prop  $\psi \subseteq \text{vars-of-prop } (\text{conn } c \ l)$ 
  using ab c unfolding binary-connectives-def by auto
next
case unary note c = this
fix  $\varphi :: 'v \text{ propo}$ 
have  $l = [\psi]$  using corr c incl split-list by force
then show vars-of-prop  $\psi \subseteq \text{vars-of-prop } (\text{conn } c \ l)$  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

```

3.1.4 Positions

Instead of 1 or 2 we use L or R

datatype *sign* = $L \mid R$

We use *nil* instead of ε .

fun *pos* :: $'v \text{ propo} \Rightarrow \text{sign list set}$ **where**

```

pos FF =  $\{\emptyset\} \mid$ 
pos FT =  $\{\emptyset\} \mid$ 
pos (FVar x) =  $\{\emptyset\} \mid$ 
pos (FAnd  $\varphi \ \psi$ ) =  $\{\emptyset\} \cup \{L \ \# \ p \mid p. p \in \text{pos } \varphi\} \cup \{R \ \# \ p \mid p. p \in \text{pos } \psi\} \mid$ 
pos (FOr  $\varphi \ \psi$ ) =  $\{\emptyset\} \cup \{L \ \# \ p \mid p. p \in \text{pos } \varphi\} \cup \{R \ \# \ p \mid p. p \in \text{pos } \psi\} \mid$ 
pos (FEq  $\varphi \ \psi$ ) =  $\{\emptyset\} \cup \{L \ \# \ p \mid p. p \in \text{pos } \varphi\} \cup \{R \ \# \ p \mid p. p \in \text{pos } \psi\} \mid$ 
pos (FImp  $\varphi \ \psi$ ) =  $\{\emptyset\} \cup \{L \ \# \ p \mid p. p \in \text{pos } \varphi\} \cup \{R \ \# \ p \mid p. p \in \text{pos } \psi\} \mid$ 
pos (FNot  $\varphi$ ) =  $\{\emptyset\} \cup \{L \ \# \ p \mid p. p \in \text{pos } \varphi\}$ 

```

lemma *finite-pos*: *finite* (*pos* φ)

by (*induct* φ , *auto*)

lemma *finite-inj-comp-set*:

```

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

```

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

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

next

```

fix x ::  $'v$  and s ::  $'v \text{ set}$ 
assume f: finite s and notin:  $x \notin s$ 
and IH: card  $\{f \ p \mid p. p \in s\} = \text{card } s$ 

```

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

lemma *cons-inject*:

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

lemma *finite-insert-nil-cons*:

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

lemma *cord-not[simp]*:

card (pos (FNot φ)) = 1 + card (pos φ)
by (*simp add: cons-inject finite-inj-comp-set finite-pos*)

lemma *card-seperate*:

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

proof –

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

qed

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

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

fixes $\varphi :: 'v\ \text{propo}$
shows $\text{card } (\text{vars-of-prop } \varphi) \leq \text{prop-size } \varphi$

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

proof –

fix $\varphi1\ \varphi2 :: 'v\ \text{propo}$
assume *IH1: card (vars-of-prop $\varphi1$) \leq card (pos $\varphi1$)*
and *IH2: card (vars-of-prop $\varphi2$) \leq card (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*
then have $\dots \geq \text{card } (\text{vars-of-prop } \varphi1 \cup \text{vars-of-prop } \varphi2)$ **using** *card-Un-le le-trans* **by** *blast*
ultimately
show $\text{card } (\text{vars-of-prop } \varphi1 \cup \text{vars-of-prop } \varphi2) \leq \text{Suc } (\text{card } (?L \cup ?R))$
 $\text{card } (\text{vars-of-prop } \varphi1 \cup \text{vars-of-prop } \varphi2) \leq \text{Suc } (\text{card } (?L \cup ?R))$
 $\text{card } (\text{vars-of-prop } \varphi1 \cup \text{vars-of-prop } \varphi2) \leq \text{Suc } (\text{card } (?L \cup ?R))$

```

      card (vars-of-prop  $\varphi 1 \cup$  vars-of-prop  $\varphi 2$ )  $\leq$  Suc (card (?L  $\cup$  ?R))
    by auto
  qed

```

```

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

```

```

inductive path-to :: sign list  $\Rightarrow$  'v propo  $\Rightarrow$  'v propo  $\Rightarrow$  bool where
  path-to-refl[intro]: path-to []  $\varphi$   $\varphi$  |
  path-to-l:  $c \in$  binary-connectives  $\vee c =$  CNot  $\Longrightarrow$  wf-conn c ( $\varphi \# l$ )  $\Longrightarrow$  path-to p  $\varphi$   $\varphi' \Longrightarrow$ 
    path-to (L#p) (conn c ( $\varphi \# l$ ))  $\varphi'$  |
  path-to-r:  $c \in$  binary-connectives  $\Longrightarrow$  wf-conn c ( $\psi \# \varphi \# []$ )  $\Longrightarrow$  path-to p  $\varphi$   $\varphi' \Longrightarrow$ 
    path-to (R#p) (conn c ( $\psi \# \varphi \# []$ ))  $\varphi'$ 

```

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

lemma path-to-subformula:

```

  path-to p  $\varphi$   $\varphi' \Longrightarrow \varphi' \preceq \varphi$ 
apply (induct rule: path-to.induct)
apply simp
apply (metis list.set-intros(1) subformula-into-subformula)
using subformula-trans subformula-in-binary-conn(2) by metis

```

lemma subformula-path-exists:

```

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

```

proof (induct rule: subformula.induct)

```

  case subformula-refl
  have path-to []  $\varphi'$   $\varphi'$  by auto
  then show  $\exists p. \text{path-to } p \varphi' \varphi'$  by metis

```

next

```

  case (subformula-into-subformula  $\psi$  l c)
  note wf = this(2) and IH = this(4) and  $\psi =$  this(1)
  then obtain p where p: path-to p  $\psi$   $\varphi'$  by metis

```

```

  {
    fix x :: 'v
    assume  $c =$  CT  $\vee c =$  CF  $\vee c =$  CVar x
    then have False using subformula-into-subformula by auto
    then have  $\exists p. \text{path-to } p (\text{conn } c \ l) \varphi'$  by blast
  }

```

moreover {

```

  assume c: c = CNot
  then have l = [ $\psi$ ] using wf  $\psi$  wf-conn-Not-decomp by fastforce
  then have path-to (L # p) (conn c l)  $\varphi'$  by (metis c wf-conn-unary p path-to-l)
  then have  $\exists p. \text{path-to } p (\text{conn } c \ l) \varphi'$  by blast

```

}

moreover {

```

  assume c: c  $\in$  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
  then have a =  $\psi \vee b = \psi$  using  $\psi$  by auto
  then have path-to (L # p) (conn c l)  $\varphi' \vee$  path-to (R # p) (conn c l)  $\varphi'$  using c path-to-l
    path-to-r p ab by (metis wf-conn-binary)
  then have  $\exists p. \text{path-to } p (\text{conn } c \ l) \varphi'$  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 :: sign list  $\Rightarrow$  'v propo  $\Rightarrow$  'v propo  $\Rightarrow$  'v propo where
replace-at [] -  $\psi = \psi$  |
replace-at (L # l) (FAnd  $\varphi \varphi'$ )  $\psi = FAnd$  (replace-at l  $\varphi \psi$ )  $\varphi'$  |
replace-at (R # l) (FAnd  $\varphi \varphi'$ )  $\psi = FAnd$   $\varphi$  (replace-at l  $\varphi' \psi$ ) |
replace-at (L # l) (FOr  $\varphi \varphi'$ )  $\psi = FOr$  (replace-at l  $\varphi \psi$ )  $\varphi'$  |
replace-at (R # l) (FOr  $\varphi \varphi'$ )  $\psi = FOr$   $\varphi$  (replace-at l  $\varphi' \psi$ ) |
replace-at (L # l) (FEq  $\varphi \varphi'$ )  $\psi = FEq$  (replace-at l  $\varphi \psi$ )  $\varphi'$  |
replace-at (R # l) (FEq  $\varphi \varphi'$ )  $\psi = FEq$   $\varphi$  (replace-at l  $\varphi' \psi$ ) |
replace-at (L # l) (FImp  $\varphi \varphi'$ )  $\psi = FImp$  (replace-at l  $\varphi \psi$ )  $\varphi'$  |
replace-at (R # l) (FImp  $\varphi \varphi'$ )  $\psi = FImp$   $\varphi$  (replace-at l  $\varphi' \psi$ ) |
replace-at (L # l) (FNot  $\varphi$ )  $\psi = FNot$  (replace-at l  $\varphi \psi$ )

```

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

```

```

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.

theorem *deduction-theorem*:

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

proof

```

assume H:  $\varphi \models_f \psi$ 
{
  fix A
  have  $A \models FImp\ \varphi\ \psi$ 
  proof (cases  $A \models \varphi$ )
    case True
    then have  $A \models \psi$  using H unfolding evalf-def by metis
    then show  $A \models FImp\ \varphi\ \psi$  by auto
  next
    case False
    then show  $A \models FImp\ \varphi\ \psi$  by auto
  qed
}
then show  $\forall A. A \models FImp\ \varphi\ \psi$  by blast
next
assume A:  $\forall A. A \models FImp\ \varphi\ \psi$ 
show  $\varphi \models_f \psi$ 
proof (rule ccontr)
  assume  $\neg \varphi \models_f \psi$ 
  then obtain A where  $A \models \varphi$  and  $\neg A \models \psi$  using evalf-def by metis

```

```

    then have  $\neg A \models \text{FImp } \varphi \ \psi$  by auto
    then show False using A by blast
qed

```

A shorter proof:

```

lemma  $\varphi \models_f \psi \iff (\forall A. A \models \text{FImp } \varphi \ \psi)$ 
  by (simp add: evalf-def)

```

definition *same-over-set*:: $('v \Rightarrow \text{bool}) \Rightarrow ('v \Rightarrow \text{bool}) \Rightarrow 'v \text{ set} \Rightarrow \text{bool}$ **where**
same-over-set A B S = $(\forall c \in S. A \ c = B \ c)$

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

```

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

```

```

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

```

```
begin
```

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

3.3 Rewrite systems and properties

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

```

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  $\text{propo-rew-step } r \ \varphi \ \varphi' \implies \exists \psi \ \psi'. \ \psi \preceq \varphi \wedge \psi' \preceq \varphi' \wedge r \ \psi \ \psi'$ 
  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  $\psi \preceq \varphi \implies r \ \psi \ \psi' \implies (\exists \varphi'. \ \psi' \preceq \varphi' \wedge \text{propo-rew-step } r \ \psi \ \varphi')$ 
proof (induct  $\varphi$  rule: subformula.induct)
  case subformula-refl
  then have propo-rew-step  $r \ \psi \ \psi'$  using propo-rew-step.intros by auto
  moreover have  $\psi' \preceq \psi'$  using Prop-Logic.subformula-refl by auto
  ultimately show  $\exists \varphi'. \ \psi' \preceq \varphi' \wedge \text{propo-rew-step } r \ \psi \ \varphi'$  by fastforce
next
  case (subformula-into-subformula  $\psi'' \ l \ c$ )
  note IH = this(4) and  $r = \text{this}(5)$  and  $\psi'' = \text{this}(1)$  and  $wf = \text{this}(2)$  and  $\text{incl} = \text{this}(3)$ 
  then obtain  $\varphi'$  where *:  $\psi' \preceq \varphi' \wedge \text{propo-rew-step } r \ \psi'' \ \varphi'$  by metis
  moreover obtain  $\xi \ \xi' :: 'v \text{ propo list}$  where
     $l: l = \xi @ \psi'' \# \xi'$  using List.split-list  $\psi''$  by metis
  ultimately have 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  $l \ wf\text{-conn-no-arity-change-helper}$ )
  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  $A \models \text{conn } c \ l \longleftrightarrow A \models \text{conn } c \ l'$ 
proof (cases  $c$  rule: connective-cases-arity-2)
  case nullary
  then show  $(A \models \text{conn } c \ l) \longleftrightarrow (A \models \text{conn } c \ l')$  using  $wf \ wf'$  by auto
next
  case unary note  $c = \text{this}$ 
  then obtain  $a$  where  $l: l = [a]$  using  $wf\text{-conn-Not-decomp } wf$  by metis
  obtain  $a'$  where  $l': l' = [a']$  using  $wf\text{-conn-Not-decomp } wf' \ c$  by metis
  have  $A \models a \longleftrightarrow A \models a'$  using  $l \ l'$  by (metis nth-Cons-0 same)
  then show  $A \models \text{conn } c \ l \longleftrightarrow A \models \text{conn } c \ l'$  using  $l \ l' \ c$  by auto
next
  case binary note  $c = \text{this}$ 
  then obtain  $a \ b$  where  $l: l = [a, b]$ 
    using  $wf\text{-conn-bin-list-length list-length2-decomp } wf$  by metis
  obtain  $a' \ b'$  where  $l': l' = [a', b']$ 
    using  $wf\text{-conn-bin-list-length list-length2-decomp } wf' \ c$  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  $\text{rel} = \text{this}(1)$  and  $\text{IH0} = \text{this}(2)$  and  $\text{corr} = \text{this}(3)$ 
  obtain  $\psi \ \psi' \ p$  where  $\text{IH}: r \ \psi \ \psi' \wedge \text{path-to } p \ \varphi \ \psi \wedge \text{replace-at } p \ \varphi \ \psi' = \varphi'$  using IH0 by metis

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

```

3.3.2 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*

then show ?case **by** *simp*

next

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

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

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

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

}

then show $\forall A. A \models \text{conn } c (\xi @ \varphi \# \xi') \longleftrightarrow A \models \text{conn } c (\xi @ \varphi' \# \xi')$ **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 $(\text{propo-rew-step } r)^{**} \varphi \psi$ **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*)

3.3.3 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*

3.4 Transformation testing

3.4.1 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 *all-subformula-st test-symb* (*FAnd* $\varphi \psi$)
 $\longleftrightarrow (\text{test-symb } (FAnd \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
and *all-subformula-st test-symb* (*FOr* $\varphi \psi$)
 $\longleftrightarrow (\text{test-symb } (FOr \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
and *all-subformula-st test-symb* (*FNot* φ)
 $\longleftrightarrow (\text{test-symb } (FNot \varphi) \wedge \text{all-subformula-st test-symb } \varphi)$
and *all-subformula-st test-symb* (*FEq* $\varphi \psi$)
 $\longleftrightarrow (\text{test-symb } (FEq \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
and *all-subformula-st test-symb* (*FImp* $\varphi \psi$)
 $\longleftrightarrow (\text{test-symb } (FImp \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$

proof –
have *all-subformula-st test-symb* (*FAnd* $\varphi \psi$) \longleftrightarrow *all-subformula-st test-symb* (*conn CAnd* $[\varphi, \psi]$)
by *auto*
moreover have $\dots \longleftrightarrow \text{test-symb } (\text{conn } CAnd [\varphi, \psi]) \wedge (\forall \xi \in \text{set } [\varphi, \psi]. \text{all-subformula-st test-symb } \xi)$
using *all-subformula-st-decomp wf-conn-helper-facts(5)* **by** *metis*
finally show *all-subformula-st test-symb* (*FAnd* $\varphi \psi$)
 $\longleftrightarrow (\text{test-symb } (FAnd \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
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 $\dots \longleftrightarrow$
 $(\text{test-symb } (\text{conn } COr [\varphi, \psi]) \wedge (\forall \xi \in \text{set } [\varphi, \psi]. \text{all-subformula-st test-symb } \xi))$
using *all-subformula-st-decomp wf-conn-helper-facts(6)* **by** *metis*
finally show *all-subformula-st test-symb* (*FOr* $\varphi \psi$)
 $\longleftrightarrow (\text{test-symb } (FOr \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
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
 $\longleftrightarrow (\text{test-symb } (\text{conn } CEq [\varphi, \psi]) \wedge (\forall \xi \in \text{set } [\varphi, \psi]. \text{all-subformula-st test-symb } \xi))$
using *all-subformula-st-decomp wf-conn-helper-facts(8)* **by** *metis*
finally show *all-subformula-st test-symb* (*FEq* $\varphi \psi$)
 $\longleftrightarrow (\text{test-symb } (FEq \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
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
 $\longleftrightarrow (\text{test-symb } (\text{conn } CImp [\varphi, \psi]) \wedge (\forall \xi \in \text{set } [\varphi, \psi]. \text{all-subformula-st test-symb } \xi))$
using *all-subformula-st-decomp wf-conn-helper-facts(7)* **by** *metis*
finally show *all-subformula-st test-symb* (*FImp* $\varphi \psi$)
 $\longleftrightarrow (\text{test-symb } (FImp \varphi \psi) \wedge \text{all-subformula-st test-symb } \varphi \wedge \text{all-subformula-st test-symb } \psi)$
by *simp*

have *all-subformula-st test-symb* (*FNot* φ) \longleftrightarrow *all-subformula-st test-symb* (*conn CNot* $[\varphi]$)
by *auto*
moreover have $\dots = (\text{test-symb } (\text{conn } CNot [\varphi]) \wedge (\forall \xi \in \text{set } [\varphi]. \text{all-subformula-st test-symb } \xi))$
using *all-subformula-st-decomp wf-conn-helper-facts(1)* **by** *metis*
finally show *all-subformula-st test-symb* (*FNot* φ)

\longleftrightarrow (*test-symb* (*FNot* φ) \wedge *all-subformula-st test-symb* φ) **by** *simp*
qed

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

lemma *subformula-all-subformula-st*:

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

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

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

fixes *r*:: '*v* *propo* \Rightarrow '*v* *propo* \Rightarrow *bool* **and** *test-symb*:: '*v* *propo* \Rightarrow *bool* **and** *x*:: '*v*
and φ :: '*v* *propo*

assumes

test-symb-false-nullary: $\forall x. \text{test-symb } FF \wedge \text{test-symb } FT \wedge \text{test-symb } (FVar\ x) \text{ and }$
 $\forall \varphi'. \varphi' \preceq \varphi \longrightarrow (\neg \text{test-symb } \varphi') \longrightarrow (\exists \psi. r\ \varphi'\ \psi) \text{ and }$
 $\neg \text{all-subformula-st test-symb } \varphi$

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

using *assms*

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

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

then show $\exists \psi\ \psi'. \psi \preceq \varphi \wedge r\ \psi\ \psi'$

using *wf-conn-nullary test-symb-false-nullary* **by** *fastforce*

next

case (*unary* φ) **note** *IH* = *this*(1)[*OF this*(2)] **and** *r* = *this*(2) **and** *nst* = *this*(3) **and** *subf* = *this*(4)

from *r IH nst* **have** *H*: $\neg \text{all-subformula-st test-symb } \varphi \implies \exists \psi. \psi \preceq \varphi \wedge (\exists \psi'. r\ \psi\ \psi')$
by (*metis subformula-in-subformula-not subformula-refl subformula-trans*)

{

assume *n*: $\neg \text{test-symb } (FNot\ \varphi)$

obtain ψ **where** *r* (*FNot* φ) ψ **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*: *test-symb* (*FNot* φ)

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

using *all-subformula-st-decomp-explicit*(3) *nst subf* **by** *blast*

then have $\exists \psi\ \psi'. \psi \preceq FNot\ \varphi \wedge r\ \psi\ \psi'$

using *H subformula-in-subformula-not subformula-refl subformula-trans* **by** *blast*

}

ultimately show $\exists \psi\ \psi'. \psi \preceq FNot\ \varphi \wedge r\ \psi\ \psi'$ **by** *blast*

next

case (*binary* $\varphi\ \varphi1\ \varphi2$)

note *IH* $\varphi1-0$ = *this*(1)[*OF this*(4)] **and** *IH* $\varphi2-0$ = *this*(2)[*OF this*(4)] **and** *r* = *this*(4)
and φ = *this*(3) **and** *le* = *this*(5) **and** *nst* = *this*(6)

obtain *c*:: '*v* *connective* **where**

c: (*c* = *CAnd* \vee *c* = *COr* \vee *c* = *CImp* \vee *c* = *CEq*) \wedge *conn c* [$\varphi1, \varphi2$] = φ

using φ **by** *fastforce*

then have *corr*: *wf-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 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  $\text{inc}(1)$   $\text{subformula-trans le}$  by  $\text{blast}$ 
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  $\text{inc}(2)$   $\text{subformula-trans le}$  by  $\text{blast}$ 
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  $c \text{ nst}$  by  $\text{auto}$ 
show  $\exists \psi \psi'. \psi \preceq \varphi \wedge r \psi \psi'$ 
  using  $IH\varphi1$   $IH\varphi2$   $\text{subformula-trans inc subformula-refl cases le}$  by  $\text{blast}$ 
qed

```

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

Invariant while lifting of the rewriting relation

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

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

```

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

```

```

  using all-subformula-st-decomp nst by blast
then have *:  $\forall \psi. \psi \in \text{set } (\xi @ \varphi' \# \xi') \longrightarrow \text{all-subformula-st test-symb } \psi$  using  $\varphi$  sq by fastforce
then have 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 ( $\xi @ \varphi' \# \xi'$ )) using  $H'$  sq corr rel by blast

have wf-conn c ( $\xi @ \varphi' \# \xi'$ )
  by (metis wf-conn-no-arity-change-helper corr wf-conn-no-arity-change)
then show all-subformula-st test-symb (conn c ( $\xi @ \varphi' \# \xi'$ ))
  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  $\Rightarrow$  'v propo  $\Rightarrow$  bool and test-symb:: 'v propo  $\Rightarrow$  bool and x :: 'v
and  $\varphi \psi$  :: 'v 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
  propo-rew-step r  $\varphi \psi$  and
  all-subformula-st test-symb  $\varphi$ 
shows all-subformula-st test-symb  $\psi$ 
using propo-rew-step-inv-stay'[of  $\varphi$  r test-symb  $\varphi \psi$ ] assms subformula-refl by metis

```

The lemmas can be lifted to *propo-rew-step* r^\downarrow instead of *propo-rew-step*

Invariant after all rewriting

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

```

fixes r:: 'v propo  $\Rightarrow$  'v propo  $\Rightarrow$  bool and test-symb:: 'v propo  $\Rightarrow$  bool and x :: 'v
and  $\varphi \psi$  :: 'v propo
assumes
  H:  $\forall \varphi \psi. \text{propo-rew-step } r \varphi \psi \longrightarrow \text{all-subformula-st test-symb } \varphi$ 
     $\longrightarrow \text{all-subformula-st test-symb } \psi$  and
  H':  $\forall (c:: 'v \text{ connective}) \xi \varphi \xi' \varphi'. \varphi \preceq \Phi \longrightarrow \text{propo-rew-step } r \varphi \varphi'$ 
     $\longrightarrow \text{wf-conn } c (\xi @ \varphi \# \xi') \longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi \# \xi')) \longrightarrow \text{test-symb } \varphi'$ 
     $\longrightarrow \text{test-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$  and
   $\varphi \preceq \Phi$  and
  full: full (propo-rew-step r)  $\varphi \psi$  and
  init: all-subformula-st test-symb  $\varphi$ 
shows all-subformula-st test-symb  $\psi$ 
using assms unfolding full-def

```

proof –

```

have rel: (propo-rew-step r)**  $\varphi \psi$ 
  using full unfolding full-def by auto
then show all-subformula-st test-symb  $\psi$ 
  using init
  proof (induct rule: rtranclp-induct)
    case base
      then show all-subformula-st test-symb  $\varphi$  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**

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

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

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**

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

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

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*

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

using *init*

proof (*induct rule: rtrancpl-induct*)

case *base*

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

next

case (*step b c*)

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

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

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

using *propo-rew-step-inv-stay 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**

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

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

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)
then show 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 ../lib/Multiset-More
begin

```

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

3.5 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.

3.5.1 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  $\models$  FEq  $\varphi \psi \longleftrightarrow A \models$  FAnd (FImp  $\varphi \psi$ ) (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: no-equiv-def)

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

lemma no-equiv-elim-equiv-step:

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

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

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

proof –

have test-symb-false-nullary:

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

unfolding no-equiv-def by auto

moreover {

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

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

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

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

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

}

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: elim-equiv.simps)

then have $\bigwedge \varphi'. \varphi' \preceq \varphi \implies \neg \text{no-equiv-symb } \varphi' \implies \exists \psi. \text{elim-equiv } \varphi' \ \psi$ 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

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

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

lemma *elim-imp-lifted-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*:
 $\text{wf-conn } c \ l \implies \text{no-imp-symb } (\text{conn } c \ l) \longleftrightarrow c \neq \text{CImp}$
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*:
 $\text{elim-imp } \varphi \ \psi \implies \text{no-equiv } \varphi \implies \text{no-equiv } \psi$
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* φ
shows *no-equiv* ψ
using *full-propo-rew-step-inv-stay-conn* [*of elim-imp no-equiv-symb* $\varphi \ \psi$] *assms elim-imp-no-equiv*

no-equiv-symb-conn-characterization **unfolding** *no-equiv-def* **by** *metis*

lemma *no-no-imp-elim-imp-step-exists*:

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

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* *connective* **and** *l*: *'v* *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 $\bigwedge \varphi. \neg \text{no-imp-symb } \varphi \implies \exists \psi. \text{elim-imp } \varphi \ \psi$

by (*case-tac* φ) (*force simp: elim-imp.simps*)+

then have $\bigwedge \varphi'. \varphi' \preceq \varphi \implies \neg \text{no-imp-symb } \varphi' \implies \exists \psi. \text{elim-imp } \varphi' \ \psi$ **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*: $\text{full } (\text{propo-rew-step } \text{elim-imp}) \ \varphi \ \psi \implies \text{no-imp } \psi$

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

3.5.3 Eliminate all the True and False in the formula

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

inductive *elimTB* **where**

ElimTB1: *elimTB* (*FAnd* φ *FT*) φ |

ElimTB1': *elimTB* (*FAnd* *FT* φ) φ |

ElimTB2: *elimTB* (*FAnd* φ *FF*) *FF* |

ElimTB2': *elimTB* (*FAnd* *FF* φ) *FF* |

ElimTB3: *elimTB* (*FOr* φ *FT*) *FT* |

ElimTB3': *elimTB* (*FOr* *FT* φ) *FT* |

ElimTB4: *elimTB* (*FOr* φ *FF*) φ |

ElimTB4': *elimTB* (*FOr* *FF* φ) φ |

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

ElimTB6: *elimTB* (*FNot* *FF*) *FT*

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

proof –

{

fix $\varphi \psi :: 'b \text{ propo}$

have $\text{elimTB } \varphi \ \psi \implies \forall A. A \models \varphi \longleftrightarrow A \models \psi$ **by** (*induction rule: elimTB.inducts*) *auto*

}

then show *?thesis* using *preserves-un-sat-def* by auto
qed

inductive *no-T-F-symb* :: 'v propo \Rightarrow bool **where**
no-T-F-symb-comp: $c \neq CF \Rightarrow c \neq CT \Rightarrow wf_conn\ c\ l \Rightarrow (\forall \varphi \in set\ l. \varphi \neq FT \wedge \varphi \neq FF)$
 $\Rightarrow no-T-F-symb\ (conn\ c\ l)$

lemma *wf-conn-no-T-F-symb-iff[simp]*:
 $wf_conn\ c\ \psi s \Rightarrow$
 $no-T-F-symb\ (conn\ c\ \psi s) \longleftrightarrow (c \neq CF \wedge c \neq CT \wedge (\forall \psi \in set\ \psi s. \psi \neq FF \wedge \psi \neq FT))$
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]*:
 $no-T-F-symb\ (FAnd\ \varphi\ \psi) \longleftrightarrow (\forall \chi \in set\ [\varphi, \psi]. \chi \neq FF \wedge \chi \neq FT)$
 $no-T-F-symb\ (FOr\ \varphi\ \psi) \longleftrightarrow (\forall \chi \in set\ [\varphi, \psi]. \chi \neq FF \wedge \chi \neq FT)$
 $no-T-F-symb\ (FEq\ \varphi\ \psi) \longleftrightarrow (\forall \chi \in set\ [\varphi, \psi]. \chi \neq FF \wedge \chi \neq FT)$
 $no-T-F-symb\ (FImp\ \varphi\ \psi) \longleftrightarrow (\forall \chi \in set\ [\varphi, \psi]. \chi \neq FF \wedge \chi \neq FT)$
apply (*metis* *conn.simps(36)* *conn.simps(37)* *conn.simps(5)* *propo.distinct(19)*)
 $wf_conn_helper_facts(5)\ wf_conn_no-T-F-symb_iff)$
apply (*metis* *conn.simps(36)* *conn.simps(37)* *conn.simps(6)* *propo.distinct(22)*)
 $wf_conn_helper_facts(6)\ wf_conn_no-T-F-symb_iff)$
using *wf-conn-no-T-F-symb-iff* **apply** *fastforce*
by (*metis* *conn.simps(36)* *conn.simps(37)* *conn.simps(7)* *propo.distinct(23)* *wf-conn-helper-facts(7)*)
 $wf_conn_no-T-F-symb_iff)$

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

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

lemma *no-T-F-symb-fnot-imp*:
 $\neg no-T-F-symb\ (FNot\ \varphi) \Rightarrow \varphi = FT \vee \varphi = FF$
proof (*rule ccontr*)
assume $n: \neg no-T-F-symb\ (FNot\ \varphi)$
assume $\neg (\varphi = FT \vee \varphi = FF)$
then have $\forall \varphi' \in set\ [\varphi]. \varphi' \neq FT \wedge \varphi' \neq FF$ **by** *auto*
moreover have $wf_conn\ CNot\ [\varphi]$ **by** *simp*
ultimately have $no-T-F-symb\ (FNot\ \varphi)$
using *no-T-F-symb.intros* **by** (*metis* *conn.simps(4)* *connective.distinct(5,17)*)

then show *False* **using** *n* **by** *blast*
qed

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

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

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

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

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

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

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

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

lemma *no-T-F-symb-except-top-level-false-not[simp]*:
fixes $\varphi \psi$:: '*v* *propo*
assumes $\varphi = FT \vee \varphi = FF$
shows

\neg *no-T-F-symb-except-toplevel* (*FNot* φ)
by (*simp add: assms no-T-F-symb-except-toplevel.simps*)

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

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

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

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

lemma *no-T-F-except-top-level-false*:
fixes $l :: 'v$ *propo list* **and** $c :: 'v$ *connective*
assumes *wf-conn* c l
and $FT \in \text{set } l \vee FF \in \text{set } l$
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 $\varphi \psi :: 'v$ *propo*
assumes $\varphi = FT \vee \psi = FT \vee \varphi = FF \vee \psi = FF$
shows
 \neg *no-T-F-except-top-level* (*FAnd* $\varphi \psi$)
 \neg *no-T-F-except-top-level* (*FOr* $\varphi \psi$)
 \neg *no-T-F-except-top-level* (*FEq* $\varphi \psi$)
 \neg *no-T-F-except-top-level* (*FImp* $\varphi \psi$)
by (*metis all-subformula-st-test-symb-true-phi assms no-T-F-except-top-level-def*
no-T-F-symb-except-top-level-false-example)+

lemma *no-T-F-symb-except-toplevel-no-T-F-symb*:
no-T-F-symb-except-toplevel $\varphi \implies \varphi \neq FF \implies \varphi \neq FT \implies$ *no-T-F-symb* φ
by (*induct rule: no-T-F-symb-except-toplevel.induct, auto*)

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

lemma *no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb*:
no-T-F-except-top-level $\varphi \implies \varphi \neq FF \implies \varphi \neq FT \implies$ *no-T-F* φ
unfolding *no-T-F-except-top-level-def no-T-F-def* **apply** (*induct* φ)
using *no-T-F-symb-fnot* **by** *fastforce*+

lemma *no-T-F-no-T-F-except-top-level*:
no-T-F $\varphi \implies$ *no-T-F-except-top-level* φ
unfolding *no-T-F-except-top-level-def no-T-F-def*
unfolding *all-subformula-st-def* **by** *auto*

lemma *no-T-F-except-top-level-simp*[*simp*]: *no-T-F-except-top-level* FF *no-T-F-except-top-level* FT
unfolding *no-T-F-except-top-level-def* **by** *auto*

lemma *no-T-F-no-T-F-except-top-level'*[*simp*]:
no-T-F-except-top-level $\varphi \longleftrightarrow (\varphi = FF \vee \varphi = FT \vee$ *no-T-F* $\varphi)$
using *no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb no-T-F-no-T-F-except-top-level*
by *auto*

lemma *no-T-F-bin-decomp*[simp]:
assumes *c*: *c* ∈ *binary-connectives*
shows *no-T-F* (*conn c* [*φ*, *ψ*]) \longleftrightarrow (*no-T-F* *φ* ∧ *no-T-F* *ψ*)
proof –
have *wf*: *wf-conn c* [*φ*, *ψ*] **using** *c* **by** *auto*
then have *no-T-F* (*conn c* [*φ*, *ψ*]) \longleftrightarrow (*no-T-F-symb* (*conn c* [*φ*, *ψ*]) ∧ *no-T-F* *φ* ∧ *no-T-F* *ψ*)
by (*simp add: all-subformula-st-decomp no-T-F-def*)
then show *no-T-F* (*conn c* [*φ*, *ψ*]) \longleftrightarrow (*no-T-F* *φ* ∧ *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* ∨ *c* = *COr* ∨ *c* = *CEq* ∨ *c* = *CImp*
shows *no-T-F* (*conn c* [*φ*, *ψ*]) \longleftrightarrow (*no-T-F* *φ* ∧ *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 *φ ψ* :: '*v* *propo*
shows
no-T-F (*FAnd* *φ ψ*) \longleftrightarrow (*no-T-F* *φ* ∧ *no-T-F* *ψ*)
no-T-F (*FOr* *φ ψ*) \longleftrightarrow (*no-T-F* *φ* ∧ *no-T-F* *ψ*)
no-T-F (*FEq* *φ ψ*) \longleftrightarrow (*no-T-F* *φ* ∧ *no-T-F* *ψ*)
no-T-F (*FImp* *φ ψ*) \longleftrightarrow (*no-T-F* *φ* ∧ *no-T-F* *ψ*)
using *conn.simps(5–8) no-T-F-bin-decomp-expanded* **by** (*metis (no-types)*)⁺

lemma *no-T-F-comp-not*[simp]:
fixes *φ ψ* :: '*v* *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 *φ ψ* :: '*v* *propo*
assumes *φ*: *no-T-F* (*FAnd* *φ ψ*) ∨ *no-T-F* (*FOr* *φ ψ*) ∨ *no-T-F* (*FEq* *φ ψ*) ∨ *no-T-F* (*FImp* *φ ψ*)
shows *no-T-F* *ψ* **and** *no-T-F* *φ*
using *assms* **by** *auto*

lemma *no-T-F-decomp-not*:
fixes *φ* :: '*v* *propo*
assumes *φ*: *no-T-F* (*FNot* *φ*)
shows *no-T-F* *φ*
using *assms* **by** *auto*

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

```

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

```

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

```

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

```

proof –

```

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

```

moreover {

```

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

```

}

moreover {

```

  fix x :: 'v
  have H': no-T-F-except-top-level FT no-T-F-except-top-level FF
    no-T-F-except-top-level (FVar x)
    by (auto simp: no-T-F-except-top-level-def test-symb-false-nullary)

```

}

moreover {

```

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

```

}

ultimately show ?thesis

```

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

```

qed

lemma elimTB-inv:

```

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

```

proof –

{

```

  fix  $\varphi \psi :: 'v$  propo
  have H: elimTB  $\varphi \psi \implies \text{no-equiv } \varphi \implies \text{no-equiv } \psi$ 

```

```

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

```

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

3.5.4 PushNeg

Push the negation inside the formula, until the literal.

inductive pushNeg **where**

```

PushNeg1[simp]: pushNeg (FNot (FAnd  $\varphi \psi$ )) (FOr (FNot  $\varphi$ ) (FNot  $\psi$ )) |
PushNeg2[simp]: pushNeg (FNot (FOr  $\varphi \psi$ )) (FAnd (FNot  $\varphi$ ) (FNot  $\psi$ )) |
PushNeg3[simp]: pushNeg (FNot (FNot  $\varphi$ ))  $\varphi$ 

```

lemma pushNeg-transformation-consistent:

```

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

```

lemma pushNeg-explicit: 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* φ) *auto*

lemma *subformula-conn-decomp-simple*:

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

assumes *s*: *simple* ψ

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

proof –

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

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

then show $\varphi \preceq FNot\ \psi \longleftrightarrow (\varphi = FNot\ \psi \vee \varphi = \psi)$ **using** *s* **by** (*auto simp: 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: subformula-conn-decomp-simple*)

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

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

simple-not-symb - = *True*

definition *simple-not* **where**

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

declare *simple-not-def[simp]*

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

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

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

by *auto*

lemma *simple-not-step-exists*:

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

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

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

apply (*induct* ψ , *auto*)

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

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

lemma *simple-not-rew*:

fixes $\varphi :: 'v\ propo$

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

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

proof –

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

moreover {

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

have *H*: $pushNeg\ (conn\ c\ l)\ \psi \implies \neg simple-not-symb\ (conn\ c\ l)$

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*:

```

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

```

lemma *no-T-F-except-top-level-pushNeg2*:

```

 $\text{no-T-F-except-top-level } (FNot\ (FOr\ \varphi\ \psi)) \implies \text{no-T-F-except-top-level } (FAnd\ (FNot\ \varphi)\ (FNot\ \psi))$ 
by auto

```

lemma *no-T-F-symb-pushNeg*:

```

 $\text{no-T-F-symb } (FOr\ (FNot\ \varphi')\ (FNot\ \psi'))$ 
 $\text{no-T-F-symb } (FAnd\ (FNot\ \varphi')\ (FNot\ \psi'))$ 
 $\text{no-T-F-symb } (FNot\ (FNot\ \varphi'))$ 
by auto

```

lemma *propo-rew-step-pushNeg-no-T-F-symb*:

```

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

```

then have $\forall \psi \in \text{set } (\xi @ \varphi' \# \xi'). \psi \neq FF \wedge \psi \neq FT$ 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 $\varphi \psi \implies \text{no-T-F } \varphi \implies \text{no-T-F } \psi$

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

case *global-rel*

then show *?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 ($\xi @ \varphi' \# \xi'$))

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

by (*fastforce simp: no-T-F-def all-subformula-st-decomp wf wf'*)

qed

lemma *pushNeg-inv*:

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

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

assume *rel: propo-rew-step pushNeg* $\varphi \psi$

and *no: no-T-F-except-top-level* φ

then have *no-T-F-except-top-level* ψ

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*

then have *no-T-F-except-top-level* ψ **by** *blast*

}

moreover {

assume $\varphi \neq FT \wedge \varphi \neq FF$

then have *no-T-F* φ

by (*metis no no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb*)

then have *no-T-F* ψ

using *propo-rew-step-pushNeg-no-T-F rel* **by** *auto*

then have *no-T-F-except-top-level* ψ **by** (*simp add: no-T-F-no-T-F-except-top-level*)

}

ultimately show *no-T-F-except-top-level* ψ **by** *metis*

qed

}


```

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

```

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

```

fixes  $\varphi \psi :: 'v \text{ propo}$ 
assumes
   $\text{no-equiv } \varphi$  and
   $\text{no-imp } \varphi$  and

```

full (propo-rew-step pushNeg) $\varphi \psi$ and
no-T-F-except-top-level φ
shows *simple-not ψ*
using *assms full-propo-rew-step-subformula pushNeg-inv(1,2) simple-not-rew by blast*

3.5.5 Push inside

inductive *push-conn-inside* :: '*v* *connective* \Rightarrow '*v* *connective* \Rightarrow '*v* *propo* \Rightarrow '*v* *propo* \Rightarrow *bool*
for *c c'* :: '*v* *connective* **where**
push-conn-inside-l[simp]: $c = CAnd \vee c = COr \Longrightarrow c' = CAnd \vee c' = COr$
 \Longrightarrow *push-conn-inside c c' (conn c [conn c' [$\varphi 1$, $\varphi 2$], ψ])*
 $(conn c' [conn c [\varphi 1, ψ], conn c [\varphi 2, ψ]]) \mid$
push-conn-inside-r[simp]: $c = CAnd \vee c = COr \Longrightarrow c' = CAnd \vee c' = COr$
 \Longrightarrow *push-conn-inside c c' (conn c [ψ , conn c' [$\varphi 1$, $\varphi 2$]])*
 $(conn c' [conn c [ψ , $\varphi 1$], conn c [ψ , $\varphi 2$]])$

lemma *push-conn-inside-explicit:* *push-conn-inside c c' $\varphi \psi \Longrightarrow \forall A. A \models \varphi \longleftrightarrow A \models \psi$*
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 *propo-rew-step (push-conn-inside c c') FT $\psi \neg$ propo-rew-step (push-conn-inside c c') FF ψ*
proof –
 $\{$
 $\{$
fix $\varphi \psi$
have *push-conn-inside c c' $\varphi \psi \Longrightarrow \varphi = FT \vee \varphi = FF \Longrightarrow False$*
by (*induct rule: push-conn-inside.induct, auto*)
 $\}$ **note** $H = this$
fix φ
have *propo-rew-step (push-conn-inside c c') $\varphi \psi \Longrightarrow \varphi = FT \vee \varphi = FF \Longrightarrow False$*
apply (*induct rule: propo-rew-step.induct, auto simp: wf-conn-list(1) wf-conn-list(2)*)
using H **by** *blast+*
 $\}$
then show
 \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]: $wf\text{-}conn\ c\ [conn\ c'\ [\varphi, \varphi'], \psi] \Longrightarrow wf\text{-}conn\ c'\ [\varphi, \varphi']$
 \Longrightarrow *not-c-in-c'-symb c c' (conn c [conn c' [φ, φ'], ψ])* \mid
not-c-in-c'-symb-r[simp]: $wf\text{-}conn\ c\ [\psi, conn\ c'\ [\varphi, \varphi']] \Longrightarrow wf\text{-}conn\ c'\ [\varphi, \varphi']$
 \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:*
 $not\text{-}c\text{-}in\text{-}c'\text{-}symb\ c\ c'\ \xi \Longrightarrow \xi = FF \vee \xi = FT \vee \xi = FVar\ x \vee \xi = FNot\ FF \vee \xi = FNot\ FT$
 $\vee \xi = FNot\ (FVar\ x) \Longrightarrow False$
apply (*induct rule: not-c-in-c'-symb.induct, auto simp: 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]*:
 $\neg \text{not-c-in-c'-symb } c \ c' \ FF$
 $\neg \text{not-c-in-c'-symb } c \ c' \ FT$
 $\neg \text{not-c-in-c'-symb } c \ c' \ (FVar \ x)$
 $\neg \text{not-c-in-c'-symb } c \ c' \ (FNot \ FF)$
 $\neg \text{not-c-in-c'-symb } c \ c' \ (FNot \ FT)$
 $\neg \text{not-c-in-c'-symb } c \ c' \ (FNot \ (FVar \ x))$
using *c-in-c'-symb-simp* **by** *metis+*

definition *c-in-c'-only* **where**
c-in-c'-only $c \ c' \equiv \text{all-subformula-st } (c\text{-in-c'-symb } c \ c')$

lemma *c-in-c'-only-simp[simp]*:
 $c\text{-in-c'-only } c \ c' \ FF$
 $c\text{-in-c'-only } c \ c' \ FT$
 $c\text{-in-c'-only } c \ c' \ (FVar \ x)$
 $c\text{-in-c'-only } c \ c' \ (FNot \ FF)$
 $c\text{-in-c'-only } c \ c' \ (FNot \ FT)$
 $c\text{-in-c'-only } c \ c' \ (FNot \ (FVar \ x))$
unfolding *c-in-c'-only-def* **by** *auto*

lemma *not-c-in-c'-symb-commute*:
 $\text{not-c-in-c'-symb } c \ c' \ \xi \implies \text{wf-conn } c \ [\varphi, \psi] \implies \xi = \text{conn } c \ [\varphi, \psi]$
 $\implies \text{not-c-in-c'-symb } c \ c' \ (\text{conn } c \ [\psi, \varphi])$
proof (*induct rule: not-c-in-c'-symb.induct*)
case (*not-c-in-c'-symb-r* $\varphi' \ \varphi'' \ \psi'$) **note** $H = \text{this}$
then have $\psi: \psi = \text{conn } c' \ [\varphi'', \psi']$ **using** *conn-inj* **by** *auto*
have $\text{wf-conn } c \ [\text{conn } c' \ [\varphi'', \psi'], \varphi]$
using $H(1)$ *wf-conn-no-arity-change length-Cons* **by** *metis*
then show $\text{not-c-in-c'-symb } c \ c' \ (\text{conn } c \ [\psi, \varphi])$
unfolding ψ **using** *not-c-in-c'-symb.intros(1)* H **by** *auto*
next
case (*not-c-in-c'-symb-l* $\varphi' \ \varphi'' \ \psi'$) **note** $H = \text{this}$
then have $\varphi = \text{conn } c' \ [\varphi', \varphi'']$ **using** *conn-inj* **by** *auto*
moreover have $\text{wf-conn } c \ [\psi', \text{conn } c' \ [\varphi', \varphi'']]$
using $H(1)$ *wf-conn-no-arity-change length-Cons* **by** *metis*
ultimately show $\text{not-c-in-c'-symb } c \ c' \ (\text{conn } c \ [\psi, \varphi])$
using *not-c-in-c'-symb.intros(2)* *conn-inj not-c-in-c'-symb-l.hyps*
 $\text{not-c-in-c'-symb-l.prem}(1,2)$ **by** *blast*
qed

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

lemma *not-c-in-c'-comm*:
assumes *wf*: $\text{wf-conn } c \ [\varphi, \psi]$
shows $c\text{-in-c'-only } c \ c' \ (\text{conn } c \ [\varphi, \psi]) \longleftrightarrow c\text{-in-c'-only } c \ c' \ (\text{conn } c \ [\psi, \varphi])$ (**is** $?A \longleftrightarrow ?B$)
proof –
have $?A \longleftrightarrow (c\text{-in-c'-symb } c \ c' \ (\text{conn } c \ [\varphi, \psi]) \wedge (\forall \xi \in \text{set } [\varphi, \psi]. \text{all-subformula-st } (c\text{-in-c'-symb } c \ c' \ \xi)))$
using *all-subformula-st-decomp wf* **unfolding** *c-in-c'-only-def* **by** *fastforce*
also have $\dots \longleftrightarrow (c\text{-in-c'-symb } c \ c' \ (\text{conn } c \ [\psi, \varphi]))$

```

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

```

```

lemma not-c-in-c'-simp[simp]:
  fixes  $\varphi 1 \ \varphi 2 \ \psi :: 'v \text{ propo}$  and  $x :: 'v$ 
  shows
    c-in-c'-symb c c' FT
    c-in-c'-symb c c' FF
    c-in-c'-symb c c' (FVar x)
    wf-conn c [conn c'  $[\varphi 1, \varphi 2], \psi] \implies \text{wf-conn } c' [\varphi 1, \varphi 2]$ 
     $\implies \neg \text{c-in-c'-only } c \ c' (\text{conn } c [\text{conn } c' [\varphi 1, \varphi 2], \psi])$ 
  apply (simp-all add: c-in-c'-only-def)
  using all-subformula-st-test-symb-true-phi not-c-in-c'-symb-l by blast

```

```

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

```

```

lemma c-in-c'-symb-step-exists:
  fixes  $\varphi :: 'v \text{ propo}$ 
  assumes c:  $c = C\text{And } \vee \ c = C\text{Or}$  and c':  $c' = C\text{And } \vee \ c' = C\text{Or}$ 
  shows  $\psi \preceq \varphi \implies \neg \text{c-in-c'-symb } c \ c' \ \psi \implies \exists \psi'. \text{push-conn-inside } c \ c' \ \psi \ \psi'$ 
  apply (induct  $\psi$  rule: propo-induct-arity)
  apply auto[2]
proof -
  fix  $\psi 1 \ \psi 2 \ \varphi' :: 'v \text{ propo}$ 
  assume IH $\psi 1$ :  $\psi 1 \preceq \varphi \implies \neg \text{c-in-c'-symb } c \ c' \ \psi 1 \implies \text{Ex } (\text{push-conn-inside } c \ c' \ \psi 1)$ 
  and IH $\psi 2$ :  $\psi 2 \preceq \varphi \implies \neg \text{c-in-c'-symb } c \ c' \ \psi 2 \implies \text{Ex } (\text{push-conn-inside } c \ c' \ \psi 2)$ 
  and  $\varphi'$ :  $\varphi' = F\text{And } \psi 1 \ \psi 2 \vee \varphi' = F\text{Or } \psi 1 \ \psi 2 \vee \varphi' = F\text{Imp } \psi 1 \ \psi 2 \vee \varphi' = F\text{Eq } \psi 1 \ \psi 2$ 
  and in $\varphi$ :  $\varphi' \preceq \varphi$  and n0:  $\neg \text{c-in-c'-symb } c \ c' \ \varphi'$ 
  then have n: not-c-in-c'-symb c c'  $\varphi'$  by auto
  {
    assume  $\varphi'$ :  $\varphi' = \text{conn } c [\psi 1, \psi 2]$ 
    obtain a b where  $\psi 1 = \text{conn } c' [a, b] \vee \psi 2 = \text{conn } c' [a, b]$ 
    using n  $\varphi'$  apply (induct rule: not-c-in-c'-symb.induct)
    using c by force+
    then have  $\text{Ex } (\text{push-conn-inside } c \ c' \ \varphi')$ 
    unfolding  $\varphi'$  apply auto
    using push-conn-inside.intros(1) c c' apply blast
  }

```

```

    using push-conn-inside.intros(2) c c' by blast
  }
  moreover {
    assume  $\varphi'$ :  $\varphi' \neq \text{conn } c [\psi 1, \psi 2]$ 
    have  $\forall \varphi \ c \ ca. \exists \varphi 1 \ \psi 1 \ \psi 2 \ \psi 1' \ \psi 2' \ \varphi 2'. \text{conn } (c::'v \text{ connective}) [\varphi 1, \text{conn } ca [\psi 1, \psi 2]] = \varphi$ 
       $\vee \text{conn } c [\text{conn } ca [\psi 1', \psi 2'], \varphi 2'] = \varphi \vee c\text{-in-}c'\text{-symb } c \ ca \ \varphi$ 
    by (metis not-c-in-c'-symb.cases)
    then have  $Ex \ (\text{push-conn-inside } c \ c' \ \varphi')$ 
    by (metis (no-types) c c' n push-conn-inside-l push-conn-inside-r)
  }
  ultimately show  $Ex \ (\text{push-conn-inside } c \ c' \ \varphi')$  by blast
qed

```

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

```

  fixes  $\varphi :: 'v \text{ propo}$ 
  assumes noTB:  $\neg c\text{-in-}c'\text{-only } c \ c' \ \varphi$ 
  and c:  $c = CAnd \vee c = COr$  and c':  $c' = CAnd \vee c' = COr$ 
  shows  $\exists \psi \ \psi'. \psi \preceq \varphi \wedge \text{push-conn-inside } c \ c' \ \psi \ \psi'$ 
proof -
  have test-symb-false-nullary:
     $\forall x. c\text{-in-}c'\text{-symb } c \ c' \ (FF:: 'v \text{ propo}) \wedge c\text{-in-}c'\text{-symb } c \ c' \ FT$ 
     $\wedge c\text{-in-}c'\text{-symb } c \ c' \ (FVar \ (x:: 'v))$ 
  by auto
  moreover {
    fix  $x :: 'v$ 
    have  $H': c\text{-in-}c'\text{-symb } c \ c' \ FT \ c\text{-in-}c'\text{-symb } c \ c' \ FF \ c\text{-in-}c'\text{-symb } c \ c' \ (FVar \ x)$ 
    by simp+
  }
  moreover {
    fix  $\psi :: 'v \text{ propo}$ 
    have  $\psi \preceq \varphi \implies \neg c\text{-in-}c'\text{-symb } c \ c' \ \psi \implies \exists \psi'. \text{push-conn-inside } c \ c' \ \psi \ \psi'$ 
    by (auto simp: assms(2) c' c-in-c'-symb-step-exists)
  }
  ultimately show ?thesis using noTB no-test-symb-step-exists[of c-in-c'-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  $\varphi \ \psi$ )
  then show no-T-F  $\psi$ 
  by (cases rule: push-conn-inside.cases, auto)
next
  case (propo-rew-one-step-lift  $\varphi \ \varphi' \ c \ \xi \ \xi'$ )
  note rel = this(1) and IH = this(2) and wf = this(3) and no-T-F = this(4)
  have no-T-F  $\varphi$ 
  using wf no-T-F no-T-F-def subformula-into-subformula subformula-all-subformula-st
    subformula-refl by (metis (no-types) in-set-conv-decomp)
  then have  $\varphi': \text{no-T-F } \varphi'$  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)
  then have  $n: \forall \zeta \in \text{set } (\xi @ \varphi' \ \# \ \xi'). \text{no-T-F } \zeta$  using  $\varphi'$  by auto
  then have  $n': \forall \zeta \in \text{set } (\xi @ \varphi' \ \# \ \xi'). \zeta \neq FF \wedge \zeta \neq FT$ 

```

```

using  $\varphi'$  by (metis no-T-F-symb-false(1) no-T-F-symb-false(2) no-T-F-def
  all-subformula-st-test-symb-true-phi)

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

```

lemma *simple-propo-rew-step-push-conn-inside-inv*:

```

 $propo\text{-}rew\text{-}step (push\text{-}conn\text{-}inside\ c\ c') \ \varphi \ \psi \implies simple\ \varphi \implies simple\ \psi$ 
apply (induct rule: propo-rew-step.induct)
apply (rename-tac  $\varphi$ , case-tac  $\varphi$ , auto simp: 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  $c\ c' :: 'v$  connective and  $\varphi\ \psi :: 'v$  propo
shows  $propo\text{-}rew\text{-}step (push\text{-}conn\text{-}inside\ c\ c') \ \varphi \ \psi \implies simple\text{-}not\ \varphi \implies simple\text{-}not\ \psi$ 
proof (induct rule: propo-rew-step.induct)
  case (global-rel  $\varphi\ \psi$ )
  then show ?case by (cases  $\varphi$ , auto simp: 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  $\forall \zeta \in set\ (\xi @ \varphi \# \xi').\ simple\text{-}not\ \zeta$ 
      by (metis  $wf$  all-subformula-st-decomp simple simple-not-def)
      then have  $\forall \zeta \in set\ (\xi @ \varphi' \# \xi').\ simple\text{-}not\ \zeta$  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 ($\xi @ \text{conn } c' (\chi s @ \varphi' \# \chi s') \# \xi'$)

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*: $\chi s = []$ $\chi s' = []$ **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 $c' \varphi \psi \implies \psi \neq FT \wedge \psi \neq FF$

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

lemma push-conn-inside-inv:

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

assumes full (propo-rew-step (push-conn-inside c c') $\varphi \psi$)

and no-equiv φ and no-imp φ and no-T-F-except-top-level φ and simple-not φ

shows no-equiv ψ and no-imp ψ and no-T-F-except-top-level ψ and simple-not ψ

proof –

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

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

have H: propo-rew-step (push-conn-inside c c') $\varphi \psi \implies$ all-subformula-st simple-not-symb φ
 \implies all-subformula-st simple-not-symb ψ

apply (induct $\varphi \psi$ rule: propo-rew-step.induct)

using H apply simp

proof (rename-tac $\varphi \varphi'$ ca $\psi s \psi s'$, case-tac ca rule: connective-cases-arity)

fix $\varphi \varphi' :: 'v \text{ propo}$ and c:: 'v connective and $\xi \xi' :: 'v \text{ propo list}$

and x:: 'v

assume wf-conn c ($\xi @ \varphi \# \xi'$)

and $c = CT \vee c = CF \vee c = CVar x$

then have $\xi @ \varphi \# \xi' = []$ by auto

then have False by auto

then show all-subformula-st simple-not-symb (conn c ($\xi @ \varphi' \# \xi'$)) by blast

next

fix $\varphi \varphi' :: 'v \text{ propo}$ and ca:: 'v connective and $\xi \xi' :: 'v \text{ propo list}$

and x:: 'v

assume rel: propo-rew-step (push-conn-inside c c') $\varphi \varphi'$

and $\varphi\text{-}\varphi'$: all-subformula-st simple-not-symb $\varphi \implies$ all-subformula-st simple-not-symb φ'

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: $\xi = [] \wedge \xi' = []$ using c corr by auto

then have simple-not:all-subformula-st simple-not-symb (FNot φ) using corr c n by auto

then have simple φ

using all-subformula-st-test-symb-true-phi simple-not-symb.simps(1) by blast

then have simple φ'

using rel simple-propo-rew-step-push-conn-inside-inv by blast

then show 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 $\varphi \varphi' :: 'v \text{ propo}$ and ca:: 'v connective and $\xi \xi' :: 'v \text{ propo list}$

and x:: 'v

assume rel: propo-rew-step (push-conn-inside c c') $\varphi \varphi'$

and $n\varphi$: all-subformula-st simple-not-symb $\varphi \implies$ all-subformula-st simple-not-symb φ'

and corr: wf-conn ca ($\xi @ \varphi \# \xi'$)

and n: all-subformula-st simple-not-symb (conn ca ($\xi @ \varphi \# \xi'$))

and c: ca \in binary-connectives


```

have all-subformula-st simple-not-symb  $\varphi$ 
  using  $n$   $c$  corr all-subformula-st-decomp by fastforce
then have  $\varphi'$ : 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
then have  $\xi @ \varphi' \# \xi' = [a, \varphi'] \vee (\xi @ \varphi' \# \xi') = [\varphi', b]$ 
  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
  then have 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))
}
then have  $\forall \varphi. \varphi \in \text{set } (\xi @ \varphi' \# \xi') \longrightarrow \text{all-subformula-st simple-not-symb } \varphi$ 
  by (metis (no-types))

moreover have simple-not-symb (conn  $ca$   $(\xi @ \varphi' \# \xi')$ )
  using  $ab$  conn-inj-not(1) corr wf-conn-list-decomp(4) wf-conn-no-arity-change
    not-Cons-self2 self-append-conv2 simple-not-symb.elims(3) by (metis (no-types) c
    calculation(1) wf-conn-binary)
moreover have wf-conn  $ca$   $(\xi @ \varphi' \# \xi')$  using  $c$  calculation(1) by auto
ultimately show all-subformula-st simple-not-symb (conn  $ca$   $(\xi @ \varphi' \# \xi')$ )
  by (metis all-subformula-st-decomp-imp)
qed
}
moreover {
  fix  $ca :: 'v$  connective and  $\xi \xi' :: 'v$  propo list and  $\varphi \varphi' :: 'v$  propo
  have propo-rew-step (push-conn-inside  $c$   $c'$ )  $\varphi \varphi' \Longrightarrow wf\text{-conn } ca (\xi @ \varphi \# \xi')$ 
     $\Longrightarrow \text{simple-not-symb } (\text{conn } ca (\xi @ \varphi \# \xi')) \Longrightarrow \text{simple-not-symb } \varphi'$ 
     $\Longrightarrow \text{simple-not-symb } (\text{conn } ca (\xi @ \varphi' \# \xi'))$ 
  by (metis append-self-conv2 conn.simps(4) conn-inj-not(1) simple-not-symb.elims(3)
    simple-not-symb.simps(1) simple-propo-rew-step-push-conn-inside-inv
    wf-conn-no-arity-change-helper wf-conn-list-decomp(4) wf-conn-no-arity-change)
}
ultimately show simple-not  $\psi$ 
  using full-propo-rew-step-inv-stay'[of push-conn-inside c c' simple-not-symb] assms
  unfolding no-T-F-except-top-level-def simple-not-def full-unfold by metis
next
{
  fix  $\varphi \psi :: 'v$  propo
  have  $H$ : propo-rew-step (push-conn-inside  $c$   $c'$ )  $\varphi \psi \Longrightarrow \text{no-T-F-except-top-level } \varphi$ 
     $\Longrightarrow \text{no-T-F-except-top-level } \psi$ 
  proof –
    assume  $rel$ : propo-rew-step (push-conn-inside  $c$   $c'$ )  $\varphi \psi$ 
    and no-T-F-except-top-level  $\varphi$ 
    then have no-T-F  $\varphi \vee \varphi = FF \vee \varphi = FT$ 
      by (metis no-T-F-symb-except-tolevel-all-subformula-st-no-T-F-symb)
    moreover {
      assume  $\varphi = FF \vee \varphi = FT$ 
      then have False using rel propo-rew-step-push-conn-inside by blast
    }
  }

```

```

    then have no-T-F-except-top-level  $\psi$  by blast
  }
  moreover {
    assume no-T-F  $\varphi \wedge \varphi \neq FF \wedge \varphi \neq FT$ 
    then have no-T-F  $\psi$  using rel push-conn-insidec-in-c'-symb-no-T-F by blast
    then have no-T-F-except-top-level  $\psi$  using no-T-F-no-T-F-except-top-level by blast
  }
  ultimately show no-T-F-except-top-level  $\psi$  by blast
qed
}
moreover {
  fix ca :: 'v connective and  $\xi \xi' :: 'v$  propo list and  $\varphi \varphi' :: 'v$  propo
  assume rel: propo-rew-step (push-conn-inside c c')  $\varphi \varphi'$ 
  assume corr: wf-conn ca ( $\xi @ \varphi \# \xi'$ )
  then have 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
    then have  $\varphi \neq FT \wedge \varphi \neq FF$  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)
    then have  $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi'). \zeta \neq FT \wedge \zeta \neq FF$  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)
}
then show 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)
}
then show no-imp  $\psi$ 
using full-propo-rew-step-inv-stay-conn[of push-conn-inside c c' no-imp-symb] assms
no-imp-symb-conn-characterization unfolding no-imp-def by metis

```

qed

lemma *push-conn-inside-full-propo-rew-step*:
fixes $\varphi \ \psi :: 'v \text{ propo}$
assumes
 no-equiv 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* $c \ c' \ \psi$
using *c-in-c'-symb-rew* *assms* *full-propo-rew-step-subformula* **by** *blast*

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

inductive *only-c-inside-symb* :: *'v connective* \Rightarrow *'v propo* \Rightarrow *bool* **for** $c :: 'v \text{ connective}$ **where**
simple-only-c-inside[*simp*]: *simple* $\varphi \Longrightarrow$ *only-c-inside-symb* $c \ \varphi$ |
simple-cnot-only-c-inside[*simp*]: *simple* $\varphi \Longrightarrow$ *only-c-inside-symb* $c \ (FNot \ \varphi)$ |
only-c-inside-into-only-c-inside: *wf-conn* $c \ l \Longrightarrow$ *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* ψ
 $\vee (\exists \ \varphi'. \ \psi = FNot \ \varphi' \wedge \text{simple } \varphi')$
 $\vee (\exists \ l. \ \psi = conn \ c \ l \wedge \text{wf-conn } c \ l)$)
by (*auto simp: only-c-inside-symb.intros(3)*) (*induct rule: only-c-inside-symb.induct, auto*)

lemma *only-c-inside-symb-decomp-not*[*simp*]:
fixes $c :: 'v \text{ connective}$
assumes $c: c \neq CNot$
shows *only-c-inside-symb* $c \ (FNot \ \psi) \longleftrightarrow$ *simple* ψ
apply (*auto simp: only-c-inside-symb.intros(3)*)
by (*induct FNot* ψ *rule: only-c-inside-symb.induct, auto simp: 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* ψ
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 $c \ \varphi \longleftrightarrow$
 $(\forall \psi. \ \psi \preceq \varphi \longrightarrow (\text{simple } \psi \vee (\exists \ \varphi'. \ \psi = FNot \ \varphi' \wedge \text{simple } \varphi')$
 $\vee (\exists \ l. \ \psi = conn \ c \ l \wedge \text{wf-conn } c \ l)))$
unfolding *only-c-inside-def* **by** (*auto simp: 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 $? \psi = \text{conn } c'\ l$
have *simple* $? \psi \vee (\exists \varphi'. ? \psi = FNot\ \varphi' \wedge \text{simple } \varphi') \vee (\exists l. ? \psi = \text{conn } c\ l \wedge \text{wf-conn } c\ l)$
using *only-c-inside-decomp* *only incl* **by** *blast*
moreover **have** $\neg \text{simple } ? \psi$
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** $? \psi = \text{conn } c\ l \wedge \text{wf-conn } c\ l$ **by** *metis*
then have $c = c'$ **using** *conn-inj wf* **by** *metis*
then show *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* $c\ \varphi \implies \text{c-in-c'-symb } c\ c'\ \varphi$
apply (*rule ccontr*)
apply (*cases rule: not-c-in-c'-symb.cases, auto*)
by (*metis* $\delta\ c\ c'$ *connective.distinct*(37,39) *list.distinct*(1) *only-c-inside-c-c'-false*
subformula-in-binary-conn(1,2) *wf-conn.simps*)+

lemma *c-in-c'-symb-decomp-level1*:

fixes $l :: 'v\ propo\ list$ **and** $c\ c'\ ca :: 'v\ connective$
shows *wf-conn* $ca\ l \implies ca \neq c \implies \text{c-in-c'-symb } c\ c'\ (\text{conn } ca\ l)$

proof –

have *not-c-in-c'-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: conn-inj*)
then show *wf-conn* $ca\ l \implies ca \neq c \implies \text{c-in-c'-symb } c\ c'\ (\text{conn } ca\ l)$ **by** *blast*

qed

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

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

using *inv*

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

case (*nullary x*)

```

then show ?case by (auto simp: wf-conn-list assms)
next
case (unary  $\varphi$  la)
then have  $c = CNot \wedge la = [\varphi]$  by (metis (no-types) wf-conn-list(8))
then show ?case using assms(2) assms(1) by blast
next
case (binary  $\varphi1$   $\varphi2$ )
note  $IH\varphi1 = this(1)$  and  $IH\varphi2 = this(2)$  and  $\varphi = this(3)$  and  $only = this(5)$  and  $wf = this(4)$ 
and  $no-equiv = this(6)$  and  $no-imp = this(7)$  and  $simple-not = this(8)$ 
then have  $l: l = [\varphi1, \varphi2]$  by (meson wf-conn-list(4-7))
let ? $\varphi = conn$   $c$   $l$ 

obtain  $c1$   $l1$   $c2$   $l2$  where  $\varphi1: \varphi1 = conn$   $c1$   $l1$  and  $wf\varphi1: wf-conn$   $c1$   $l1$ 
and  $\varphi2: \varphi2 = conn$   $c2$   $l2$  and  $wf\varphi2: wf-conn$   $c2$   $l2$  using exists-c-conn by metis
then have  $c-in-only\varphi1: c-in-c'-only$   $c$   $c'$  ( $conn$   $c1$   $l1$ ) and  $c-in-c'-only$   $c$   $c'$  ( $conn$   $c2$   $l2$ )
using only  $l$  unfolding  $c-in-c'-only-def$  using assms(1) by auto
have  $inc\varphi1: \varphi1 \preceq ?\varphi$  and  $inc\varphi2: \varphi2 \preceq ?\varphi$ 
using  $\varphi1$   $\varphi2$   $\varphi$  local.wf by (metis conn.simps(5-8) helper-fact subformula-in-binary-conn(1,2))+

have  $c1-eq: c1 \neq CEq$  and  $c2-eq: c2 \neq CEq$ 
unfolding no-equiv-def using  $inc\varphi1$   $inc\varphi2$  by (metis  $\varphi1$   $\varphi2$   $wf\varphi1$   $wf\varphi2$  assms(1) no-equiv
no-equiv-eq(1) no-equiv-symb.elims(3) no-equiv-symb-conn-characterization wf-conn-list(4,5)
no-equiv-def subformula-all-subformula-st)+
have  $c1-imp: c1 \neq CImp$  and  $c2-imp: c2 \neq CImp$ 
using no-imp by (metis  $\varphi1$   $\varphi2$  all-subformula-st-decomp-explicit-imp(2,3) assms(1)
conn.simps(5,6)  $l$  no-imp-imp(1) no-imp-symb.elims(3) no-imp-symb-conn-characterization
 $wf\varphi1$   $wf\varphi2$  all-subformula-st-decomp no-imp-symb-conn-characterization)+
have  $c1c: c1 \neq c'$ 
proof
assume  $c1c: c1 = c'$ 
then obtain  $\xi1$   $\xi2$  where  $l1: l1 = [\xi1, \xi2]$ 
by (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
then have  $(\varphi1 = conn$   $c$   $l1 \wedge wf-conn$   $c$   $l1) \vee (\exists \psi1. \varphi1 = FNot$   $\psi1) \vee simple$   $\varphi1$ 
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  $\varphi1 = conn$   $c$   $l1 \wedge wf-conn$   $c$   $l1$ 
then have 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  $\exists \psi1. \varphi1 = FNot$   $\psi1$ 
then obtain  $\psi1$  where  $\varphi1 = FNot$   $\psi1$  by metis
then have 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  $\varphi1$ 

```

```

then have only-c-inside  $c \varphi 1$ 
  by (metis all-subformula-st-decomp-explicit(3) assms(1) connective.distinct(37,39)
    only-c-inside-decomp-not only-c-inside-def)
}
ultimately have only-c-inside $\varphi 1$ : only-c-inside  $c \varphi 1$  by metis

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

```

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))*

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)*)

3.6 The full transformations

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

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* $\varphi \Longrightarrow$ *grouped-by* c φ |
simple-not-is-grouped[simp]: *simple* $\varphi \Longrightarrow$ *grouped-by* c (FNot φ) |
connected-is-group[simp]: *grouped-by* c $\varphi \Longrightarrow$ *grouped-by* c $\psi \Longrightarrow$ wf-conn c [φ , ψ]
 \Longrightarrow *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' [$\varphi 1$, $\varphi 2$]) \Longrightarrow $c' = CAnd \vee c' = COr \Longrightarrow$ wf-conn c' [$\varphi 1$, $\varphi 2$]
 \Longrightarrow $c' = c$
by (induct conn c' [$\varphi 1$, $\varphi 2$] rule: *only-c-inside-symb.induct*, auto *simp: conn-inj*)

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

only-c-inside c (conn c' [$\varphi 1$, $\varphi 2$]) \Longrightarrow $c' = CAnd \vee c' = COr \Longrightarrow$ wf-conn c' [$\varphi 1$, $\varphi 2$] \Longrightarrow $c = c'$
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 $\varphi \Longrightarrow$ *grouped-by* c φ (**is** ?O $\varphi \Longrightarrow$?G φ)

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

case (*nullary* φ x)
then show ?G φ **by** *auto*

next

case (*unary* ψ)
then show ?G (FNot ψ) **by** (auto *simp: c*)

next

case (*binary* φ $\varphi 1$ $\varphi 2$)
note *IH* $\varphi 1 = this(1)$ **and** *IH* $\varphi 2 = this(2)$ **and** $\varphi = this(3)$ **and** *only* = *this(4)*
have φ -conn: $\varphi = conn$ c [$\varphi 1$, $\varphi 2$] **and** wf: wf-conn c [$\varphi 1$, $\varphi 2$]
proof –
obtain c'' l'' **where** φ -c'': $\varphi = conn$ c'' l'' **and** wf: wf-conn c'' l''
using *exists-c-conn* **by** *metis*
then have 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
  then have  $c = c''$ 
    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))
  then show  $\varphi = \text{conn } c [\varphi 1, \varphi 2]$  and  $\text{wf-conn } c [\varphi 1, \varphi 2]$  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' [ $\varphi$ ,  $\psi$ ])  $\implies c \neq c' \implies \text{wf-conn } c' [\varphi, \psi] \implies \text{False}$ 
apply (induct conn c' [ $\varphi$ ,  $\psi$ ] rule: grouped-by.induct)
apply (auto simp: simple-decomp wf-conn-list, auto simp: 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 $\varphi \implies \text{super-grouped-by } c \ c' \ \varphi \mid$
 connected-is-super-group: super-grouped-by c c' $\varphi \implies \text{super-grouped-by } c \ c' \ \psi \implies \text{wf-conn } c [\varphi, \psi]$
 $\implies \text{super-grouped-by } c \ c' (\text{conn } c' [\varphi, \psi])$

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:  $c = \text{CAnd } \vee c = \text{COr}$  and c':  $c' = \text{CAnd } \vee c' = \text{COr}$  and cc':  $c \neq c'$ 
shows no-equiv  $\varphi \implies \text{no-imp } \varphi \implies \text{simple-not } \varphi \implies \text{c-in-c'-only } c \ c' \ \varphi$ 
 $\implies \text{super-grouped-by } c \ c' \ \varphi$ 
(is ?NE  $\varphi \implies ?NI \ \varphi \implies ?SN \ \varphi \implies ?C \ \varphi \implies ?S \ \varphi$ )

```

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

```

case (nullary  $\varphi$  x)
then show ?S  $\varphi$  by auto

```

next

```

case (unary  $\varphi$ )
then have simple-not-symb (FNot  $\varphi$ )
  using all-subformula-st-test-symb-true-phi unfolding simple-not-def by blast
then have  $\varphi = \text{FT} \vee \varphi = \text{FF} \vee (\exists x. \varphi = \text{FVar } x)$  by (cases  $\varphi$ , auto)
then show ?S (FNot  $\varphi$ ) by auto

```

next

```

case (binary  $\varphi$   $\varphi 1$   $\varphi 2$ )
note IH $\varphi 1 = \text{this}(1)$  and IH $\varphi 2 = \text{this}(2)$  and no-equiv = this(4) and no-imp = this(5)
and simpleN = this(6) and c-in-c'-only = this(7) and  $\varphi' = \text{this}(3)$ 
{
  assume  $\varphi = \text{FImp } \varphi 1 \ \varphi 2 \vee \varphi = \text{FEq } \varphi 1 \ \varphi 2$ 

```

```

    then have False using no-equiv no-imp by auto
    then have ?S  $\varphi$  by auto
  }
  moreover {
    assume  $\varphi$ :  $\varphi = \text{conn } c' [\varphi 1, \varphi 2] \wedge \text{wf-conn } c' [\varphi 1, \varphi 2]$ 
    have c-in-c'-only:  $c\text{-in-}c'\text{-only } c \ c' \ \varphi 1 \wedge c\text{-in-}c'\text{-only } c \ c' \ \varphi 2 \wedge c\text{-in-}c'\text{-symb } c \ c' \ \varphi$ 
      using c-in-c'-only  $\varphi'$  unfolding c-in-c'-only-def by auto
    have super-grouped-by  $c \ c' \ \varphi 1$  using  $\varphi \ c'$  no-equiv no-imp simpleN IH  $\varphi 1$  c-in-c'-only by auto
    moreover have super-grouped-by  $c \ c' \ \varphi 2$ 
      using  $\varphi \ c'$  no-equiv no-imp simpleN IH  $\varphi 2$  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  $\varphi$ :  $\varphi = \text{conn } c [\varphi 1, \varphi 2] \wedge \text{wf-conn } c [\varphi 1, \varphi 2]$ 
    then have only-c-inside  $c \ \varphi 1 \wedge \text{only-c-inside } c \ \varphi 2$ 
      using c-in-c'-symb-c-implies-only-c-inside  $c \ c' \ c\text{-in-}c'\text{-only}$  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')
    then have only-c-inside  $c \ (\text{conn } c [\varphi 1, \varphi 2])$ 
      unfolding only-c-inside-def using  $\varphi$ 
      by (simp add: only-c-inside-into-only-c-inside all-subformula-st-decomp)
    then have grouped-by  $c \ \varphi$  using  $\varphi$  only-c-inside-imp-grouped-by  $c$  by blast
    then have ?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) wf-conn-helper-facts(5,6))
qed

```

3.6.2 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 $\varphi \equiv \text{is-conj-with-TF } \varphi \wedge \text{no-T-F-except-top-level } \varphi$

Full CNF transformation

The full CNF transformation consists simply in chaining all the transformation defined before.

definition *cnf-rew* **where** *cnf-rew* =

(*full (propo-rew-step elim-equiv)*) *OO*
(*full (propo-rew-step elim-imp)*) *OO*
(*full (propo-rew-step elimTB)*) *OO*
(*full (propo-rew-step pushNeg)*) *OO*
(*full (propo-rew-step pushDisj)*)

lemma *cnf-rew-consistent*: *preserves-un-sat cnf-rew*

by (simp add: *cnf-rew-def elimEquiv-lifted-consistant elim-imp-lifted-consistant elimTB-consistent*
preserves-un-sat-OO pushDisj-consistent pushNeg-lifted-consistant)

```

lemma cnf-rew-is-cnf: cnf-rew  $\varphi$   $\varphi' \implies$  is-cnf  $\varphi'$ 
  apply (unfold cnf-rew-def OO-def)
  apply auto
proof –
  fix  $\varphi$   $\varphiEq$   $\varphiImp$   $\varphiTB$   $\varphiNeg$   $\varphiDisj$  :: 'v propo
  assume Eq: full (propo-rew-step elim-equiv)  $\varphi$   $\varphiEq$ 
  then have no-equiv: no-equiv  $\varphiEq$  using no-equiv-full-propo-rew-step-elim-equiv by blast

  assume Imp: full (propo-rew-step elim-imp)  $\varphiEq$   $\varphiImp$ 
  then have no-imp: no-imp  $\varphiImp$  using no-imp-full-propo-rew-step-elim-imp by blast
  have no-imp-inv: no-equiv  $\varphiImp$  using no-equiv Imp elim-imp-inv by blast

  assume TB: full (propo-rew-step elimTB)  $\varphiImp$   $\varphiTB$ 
  then have noTB: no-T-F-except-top-level  $\varphiTB$ 
    using no-imp-inv no-imp elimTB-full-propo-rew-step by blast
  have noTB-inv: no-equiv  $\varphiTB$  no-imp  $\varphiTB$  using elimTB-inv TB no-imp no-imp-inv by blast+

  assume Neg: full (propo-rew-step pushNeg)  $\varphiTB$   $\varphiNeg$ 
  then have noNeg: simple-not  $\varphiNeg$ 
    using noTB-inv noTB pushNeg-full-propo-rew-step by blast
  have noNeg-inv: no-equiv  $\varphiNeg$  no-imp  $\varphiNeg$  no-T-F-except-top-level  $\varphiNeg$ 
    using pushNeg-inv Neg noTB noTB-inv by blast+

  assume Disj: full (propo-rew-step pushDisj)  $\varphiNeg$   $\varphiDisj$ 
  then have no-Disj: or-in-and-only  $\varphiDisj$ 
    using noNeg-inv noNeg pushDisj-full-propo-rew-step by blast
  have noDisj-inv: no-equiv  $\varphiDisj$  no-imp  $\varphiDisj$  no-T-F-except-top-level  $\varphiDisj$ 
    simple-not  $\varphiDisj$ 
  using pushDisj-inv Disj noNeg noNeg-inv by blast+

  moreover have is-conj-with-TF  $\varphiDisj$ 
    using or-in-and-only-conjunction-in-disj noDisj-inv no-Disj by blast
  ultimately show is-cnf  $\varphiDisj$  unfolding is-cnf-def by blast
qed

```

3.6.3 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

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 φ $\varphi' \implies$ 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))

3.7 More aggressive simplifications: Removing true and false at the beginning

3.7.1 Transformation

We should remove *FT* and *FF* at the beginning and not in the middle of the algorithm. To do this, we have to use more rules (one for each connective):

inductive *elimTBFull* **where**

ElimTBFull1[simp]: elimTBFull (FAnd φ FT) φ |

ElimTBFull1'[simp]: elimTBFull (FAnd FT φ) φ |

ElimTBFull2[simp]: elimTBFull (FAnd φ FF) FF |

ElimTBFull2'[simp]: elimTBFull (FAnd FF φ) FF |

ElimTBFull3[simp]: elimTBFull (FOr φ FT) FT |

ElimTBFull3'[simp]: elimTBFull (FOr FT φ) FT |

ElimTBFull4[simp]: elimTBFull (FOr φ FF) φ |

ElimTBFull4'[simp]: elimTBFull (FOr FF φ) φ |

ElimTBFull5[simp]: elimTBFull (FNot FT) FF |

ElimTBFull5'[simp]: elimTBFull (FNot FF) FT |

ElimTBFull6-l[simp]: elimTBFull (FImp FT φ) φ |

ElimTBFull6-l'[simp]: elimTBFull (FImp FF φ) FT |

ElimTBFull6-r[simp]: elimTBFull (FImp φ FT) FT |

ElimTBFull6-r'[simp]: elimTBFull (FImp φ FF) (FNot φ) |

ElimTBFull7-l[simp]: elimTBFull (FEq FT φ) φ |

ElimTBFull7-l'[simp]: elimTBFull (FEq FF φ) (FNot φ) |

ElimTBFull7-r[simp]: elimTBFull (FEq φ FT) φ |

ElimTBFull7-r'[simp]: elimTBFull (FEq φ FF) (FNot φ)

The transformation is still consistent.

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

proof –

{
 fix φ ψ :: 'b propo

```

  have elimTBFull  $\varphi \psi \implies \forall A. A \models \varphi \longleftrightarrow A \models \psi$ 
    by (induct-tac rule: elimTBFull.inducts, auto)
}
then show ?thesis using preserves-un-sat-def by auto
qed

```

Contrary to the theorem *no-T-F-symb-except-toplevel-step-exists*, 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  $\psi \preceq \varphi \implies \neg \text{no-T-F-symb-except-toplevel } \psi \implies \exists \psi'. \text{elimTBFull } \psi \psi'$ 
proof (induct  $\psi$  rule: propo-induct-arity)
  case (nullary  $\varphi'$ )
  then have False using no-T-F-symb-except-toplevel-true no-T-F-symb-except-toplevel-false by auto
  then show Ex (elimTBFull  $\varphi'$ ) by blast
next
  case (unary  $\psi$ )
  then have  $\psi = FF \vee \psi = FT$  using no-T-F-symb-except-toplevel-not-decom by blast
  then show Ex (elimTBFull (FNot  $\psi$ )) using ElimTBFull5 ElimTBFull5' by blast
next
  case (binary  $\varphi' \psi1 \psi2$ )
  then have  $\psi1 = FT \vee \psi2 = FT \vee \psi1 = FF \vee \psi2 = FF$ 
    by (metis binary-connectives-def conn.simps(5-8) insertI1 insert-commute
      no-T-F-symb-except-toplevel-bin-decom binary.hyps(3))
  then show Ex (elimTBFull  $\varphi'$ ) using elimTBFull.intros binary.hyps(3) by blast
qed

```

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

```

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

```

3.7.2 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*: $\text{propo-rew-step elim-equiv } \varphi \psi \implies \text{no-T-F } \varphi \implies \text{no-T-F } \psi$

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

```

fix  $\varphi' :: 'v \text{ propo}$  and  $\psi' :: 'v \text{ propo}$ 
assume a1:  $\text{no-T-F } \varphi'$ 
assume a2:  $\text{elim-equiv } \varphi' \psi'$ 
have  $\forall x0\ x1. (\neg \text{elim-equiv } (x1 :: 'v \text{ propo})\ x0 \vee (\exists v2\ v3\ v4\ v5\ v6\ v7. x1 = \text{FEq } v2\ v3$ 
   $\wedge x0 = \text{FAnd } (\text{FImp } v4\ v5)\ (\text{FImp } v6\ v7) \wedge v2 = v4 \wedge v4 = v7 \wedge v3 = v5 \wedge v3 = v6))$ 
 $= (\neg \text{elim-equiv } x1\ x0 \vee (\exists v2\ v3\ v4\ v5\ v6\ v7. x1 = \text{FEq } v2\ v3$ 
   $\wedge x0 = \text{FAnd } (\text{FImp } v4\ v5)\ (\text{FImp } v6\ v7) \wedge v2 = v4 \wedge v4 = v7 \wedge v3 = v5 \wedge v3 = v6))$ 
by meson
then have  $\forall p\ pa. \neg \text{elim-equiv } (p :: 'v \text{ propo})\ pa \vee (\exists pb\ pc\ pd\ pe\ pf\ pg. p = \text{FEq } pb\ pc$ 
   $\wedge pa = \text{FAnd } (\text{FImp } pd\ pe)\ (\text{FImp } pf\ pg) \wedge pb = pd \wedge pd = pg \wedge pc = pe \wedge pc = pf)$ 
using elim-equiv.cases by force
then show  $\text{no-T-F } \psi'$  using a1 a2 by fastforce

```

next

```

fix  $\varphi' :: 'v \text{ propo}$  and  $\xi\ \xi' :: 'v \text{ propo list}$  and  $c :: 'v \text{ connective}$ 
assume rel:  $\text{propo-rew-step elim-equiv } \varphi\ \varphi'$ 
and IH:  $\text{no-T-F } \varphi \implies \text{no-T-F } \varphi'$ 
and corr:  $\text{wf-conn } c\ (\xi @ \varphi \# \xi')$ 
and no-T-F:  $\text{no-T-F } (\text{conn } c\ (\xi @ \varphi \# \xi'))$ 
{
  assume c:  $c = \text{CNot}$ 
  then have empty:  $\xi = []\ \xi' = []$  using corr by auto
  then have  $\text{no-T-F } \varphi$  using no-T-F c no-T-F-decomp-not by auto
  then have  $\text{no-T-F } (\text{conn } c\ (\xi @ \varphi' \# \xi'))$  using c empty no-T-F-comp-not IH by auto
}

```

moreover {

```

assume c:  $c \in \text{binary-connectives}$ 
obtain a b where  $\xi @ \varphi \# \xi' = [a, b]$ 
  using corr c list-length2-decomp wf-conn-bin-list-length by metis
then have  $\varphi = a \vee \varphi = b$ 
  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

```

then have φ' : $\text{no-T-F } \varphi'$ **using** *ab IH* φ **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))

then have $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi'). \text{no-T-F } \zeta$ **using** $\zeta\ \varphi'\ ab$ **by** *fastforce*

moreover

have $\forall \zeta \in \text{set } (\xi @ \varphi \# \xi'). \zeta \neq \text{FT} \wedge \zeta \neq \text{FF}$
using $\zeta\ \text{corr no-T-F no-T-F-except-top-level-false no-T-F-no-T-F-except-top-level}$ **by** *blast*

then have $\text{no-T-F-symb } (\text{conn } c\ (\xi @ \varphi' \# \xi'))$

by (*metis* $\varphi'\ l'\ ab \text{all-subformula-st-test-symb-true-phi } c \text{list.distinct(1)}$

$\text{list.set-intros(1,2) no-T-F-symb-except-toplevel-bin-decom}$

$\text{no-T-F-symb-except-toplevel-no-T-F-symb no-T-F-symb-false(1,2) no-T-F-def wf-conn-binary}$

$\text{wf-conn-list(1,2)})$

ultimately have $\text{no-T-F } (\text{conn } c\ (\xi @ \varphi' \# \xi'))$

```

    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
    then have False using corr by auto
    then have 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: wf-conn-list(1,2))
        using elim-equiv.simps by blast+
        then have no-T-F-except-top-level  $\psi$  by blast
      }
      moreover {
        assume  $\varphi \neq FT \wedge \varphi \neq FF$ 
        then have no-T-F  $\varphi$ 
          by (metis no no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb)
        then have no-T-F  $\psi$  using propo-rew-step-ElimEquiv-no-T-F rel by blast
        then have 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: 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)+
    then have  $\forall \varphi \in \text{set } (\xi @ \zeta' \# \xi'). \varphi \neq FT \wedge \varphi \neq FF$  using  $l$  by auto
    moreover have  $c \neq CT \wedge c \neq CF$  using  $\text{corr}$  by auto
    ultimately show  $\text{no-}T\text{-}F\text{-symb } (\text{conn } c (\xi @ \zeta' \# \xi'))$ 
    by (metis  $\text{corr}$  wf-conn-no-arity-change wf-conn-no-arity-change-helper no- $T\text{-}F\text{-symb-comp$ )
  qed
}
ultimately show  $\text{no-}T\text{-}F\text{-except-top-level } \psi$ 
using  $\text{full-propo-rew-step-inv-stay-with-inc}$  [of  $\text{elim-equiv no-}T\text{-}F\text{-symb-except-toplevel } \varphi$ ]
   $\text{assms subformula-refl unfolding no-}T\text{-}F\text{-except-top-level-def}$  by metis
qed

```

lemma *propo-rew-step-ElimImp-no-T-F*: $\text{propo-rew-step elim-imp } \varphi \psi \implies \text{no-}T\text{-}F \varphi \implies \text{no-}T\text{-}F \psi$

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

case (*global-rel* $\varphi' \psi'$)

then show $\text{no-}T\text{-}F \psi'$

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 $\text{rel} = \text{this}(1)$ **and** $\text{IH} = \text{this}(2)$ **and** $\text{corr} = \text{this}(3)$ **and** $\text{no-}T\text{-}F = \text{this}(4)$

{

assume $c: c = CNot$

then have *empty*: $\xi = [] \ \xi' = []$ using corr by auto

then have $\text{no-}T\text{-}F \varphi$ using $\text{no-}T\text{-}F \ c \ \text{no-}T\text{-}F\text{-decomp-not}$ by auto

then have $\text{no-}T\text{-}F (\text{conn } c (\xi @ \varphi' \# \xi'))$ using c *empty* $\text{no-}T\text{-}F\text{-comp-not IH}$ by auto

}

moreover {

assume $c: c \in \text{binary-connectives}$

then obtain $a \ b$ where $\text{ab}: \xi @ \varphi \# \xi' = [a, b]$

using $\text{corr list-length2-decomp wf-conn-bin-list-length}$ by metis

then have $\varphi: \varphi = a \vee \varphi = b$

by (*metis append-self-conv2 wf-conn-list-decomp*(4) *wf-conn-unary list.discI list.sel*(3) *nth-Cons-0 tl-append2*)

have $\zeta: \forall \zeta \in \text{set } (\xi @ \varphi \# \xi'). \text{no-}T\text{-}F \zeta$ using $\text{ab } c \ \text{propo-rew-one-step-lift.prem}$ s by auto

then have $\varphi': \text{no-}T\text{-}F \varphi'$

using $\text{ab IH } \varphi \ \text{corr no-}T\text{-}F \ \text{no-}T\text{-}F\text{-def all-subformula-st-decomp-explicit}$ 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))

then have $\forall \zeta \in \text{set } (\xi @ \varphi' \# \xi'). \text{no-}T\text{-}F \zeta$ using $\zeta \ \varphi' \ \text{ab}$ by *fastforce*

moreover

have $\text{no-}T\text{-}F (\text{last } (\xi @ \varphi' \# \xi'))$ by (*simp add: calculation*)

then have $\text{no-}T\text{-}F\text{-symb } (\text{conn } c (\xi @ \varphi' \# \xi'))$

by (*metis* $\chi \ \varphi' \ \zeta \ \text{ab all-subformula-st-test-symb-true-phi } c \ \text{last.simps list.distinct}$ (1) *list.set-intros*(1) *no-T-F-bin-decomp no-T-F-def*)

ultimately have $\text{no-}T\text{-}F (\text{conn } c (\xi @ \varphi' \# \xi'))$ using $c \ \chi$ by *fastforce*

}

moreover {

fix x

assume $c = CVar \ x \vee c = CF \vee c = CT$

then have *False* using corr by auto


```

    then have no-T-F (conn c (ξ @ φ' # ξ')) by auto
  }
  ultimately show no-T-F (conn c (ξ @ φ' # ξ')) using corr wf-conn.cases by blast
qed

```

lemma *elim-imp-inv'*:

```

  fixes φ ψ :: 'v propo
  assumes full (propo-rew-step elim-imp) φ ψ and no-T-F-except-top-level φ
  shows no-T-F-except-top-level ψ
proof -
  {
    {
      fix φ ψ :: 'v propo
      have H: elim-imp φ ψ ⇒ no-T-F-except-top-level φ ⇒ no-T-F-except-top-level ψ
        by (induct φ ψ rule: elim-imp.induct, auto)
    } note H = this
    fix φ ψ :: 'v propo
    have propo-rew-step elim-imp φ ψ ⇒ no-T-F-except-top-level φ ⇒ no-T-F-except-top-level ψ
    proof -
      assume rel: propo-rew-step elim-imp φ ψ
      and no: no-T-F-except-top-level φ
      {
        assume φ = FT ∨ φ = FF
        from rel this have False
        apply (induct rule: propo-rew-step.induct)
        by (cases rule: elim-imp.cases, auto simp: wf-conn-list(1,2))
        then have no-T-F-except-top-level ψ by blast
      }
      moreover {
        assume φ ≠ FT ∧ φ ≠ FF
        then have no-T-F φ
          by (metis no no-T-F-symb-except-toplevel-all-subformula-st-no-T-F-symb)
        then have no-T-F ψ
          using rel propo-rew-step-ElimImp-no-T-F by blast
        then have no-T-F-except-top-level ψ by (simp add: no-T-F-no-T-F-except-top-level)
      }
      ultimately show no-T-F-except-top-level ψ by metis
    qed
  }
  moreover {
    fix c :: 'v connective and ξ ξ' :: 'v propo list and ζ ζ' :: 'v propo
    assume rel: propo-rew-step elim-imp ζ ζ'
    and incl: ζ ≤ φ
    and corr: wf-conn c (ξ @ ζ # ξ')
    and no-T-F: no-T-F-symb-except-toplevel (conn c (ξ @ ζ # ξ'))
    and n: no-T-F-symb-except-toplevel ζ'
    have no-T-F-symb-except-toplevel (conn c (ξ @ ζ' # ξ'))
    proof
      have p: no-T-F-symb (conn c (ξ @ ζ # ξ'))
        by (simp add: corr no-T-F no-T-F-symb-except-toplevel-no-T-F-symb wf-conn-list(1,2))

      have l: ∀ φ ∈ set (ξ @ ζ # ξ'). φ ≠ FT ∧ φ ≠ FF
        using corr wf-conn-no-T-F-symb-iff p by blast
      from rel incl have ζ' ≠ FT ∧ ζ' ≠ FF
      apply (induction ζ ζ' 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))+
  then have  $\forall \varphi \in \text{set } (\xi @ \zeta' \# \xi'). \varphi \neq FT \wedge \varphi \neq FF$  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

```

3.7.3 The new CNF and DNF transformation

The transformation is the same as before, but the order is not the same.

definition $\text{dnf-rew}' :: 'a \text{ propo} \Rightarrow 'a \text{ propo} \Rightarrow \text{bool}$ **where**

```

dnf-rew' =
  (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 $\text{dnf-rew}'\text{-consistent}$: preserves-un-sat $\text{dnf-rew}'$

by (simp add: $\text{dnf-rew}'\text{-def}$ elimEqv-lifted-consistant elim-imp-lifted-consistant
elimTBFull-consistent preserves-un-sat-OO pushConj-consistent pushNeg-lifted-consistant)

theorem $\text{cnf-transformation-correction}$:

$\text{dnf-rew}' \varphi \varphi' \implies \text{is-dnf } \varphi'$

unfolding $\text{dnf-rew}'\text{-def}$ 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 $\text{cnf-rew}' :: 'a \text{ propo} \Rightarrow 'a \text{ propo} \Rightarrow \text{bool}$ **where**

```

cnf-rew' =
  (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 $\text{cnf-rew}'\text{-consistent}$: preserves-un-sat $\text{cnf-rew}'$

by (simp add: $\text{cnf-rew}'\text{-def}$ elimEqv-lifted-consistant elim-imp-lifted-consistant
elimTBFull-consistent preserves-un-sat-OO pushDisj-consistent pushNeg-lifted-consistant)

theorem $\text{cnf}'\text{-transformation-correction}$:

$\text{cnf-rew}' \varphi \varphi' \implies \text{is-cnf } \varphi'$

unfolding $\text{cnf-rew}'\text{-def}$ 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
theory *Prop-Logic-Multiset*
imports *../lib/Multiset-More Prop-Normalisation Partial-Clausal-Logic*
begin

3.8 Link with Multiset Version

3.8.1 Transformation to Multiset

fun *mset-of-conj* :: 'a propo \Rightarrow 'a literal multiset **where**
mset-of-conj (*FOr* φ ψ) = *mset-of-conj* φ + *mset-of-conj* ψ |
mset-of-conj (*FVar* v) = {# *Pos* v #} |
mset-of-conj (*FNot* (*FVar* v)) = {# *Neg* v #} |
mset-of-conj *FF* = {#}

fun *mset-of-formula* :: 'a propo \Rightarrow 'a literal multiset set **where**
mset-of-formula (*FAnd* φ ψ) = *mset-of-formula* φ \cup *mset-of-formula* ψ |
mset-of-formula (*FOr* φ ψ) = {*mset-of-conj* (*FOr* φ ψ)} |
mset-of-formula (*FVar* ψ) = {*mset-of-conj* (*FVar* ψ)} |
mset-of-formula (*FNot* ψ) = {*mset-of-conj* (*FNot* ψ)} |
mset-of-formula *FF* = {{#}} |
mset-of-formula *FT* = {}

3.8.2 Equisatisfiability of the two Version

lemma *is-conj-with-TF-FNot*:
is-conj-with-TF (*FNot* φ) \longleftrightarrow ($\exists v. \varphi = \text{FVar } v \vee \varphi = \text{FF} \vee \varphi = \text{FT}$)
unfolding *is-conj-with-TF-def* **apply** (*rule iffI*)
apply (*induction FNot* φ *rule: super-grouped-by.induct*)
apply (*induction FNot* φ *rule: grouped-by.induct*)
apply *simp*
apply (*cases* φ ; *simp*)
apply *auto*
done

lemma *grouped-by-COr-FNot*:
grouped-by COr (*FNot* φ) \longleftrightarrow ($\exists v. \varphi = \text{FVar } v \vee \varphi = \text{FF} \vee \varphi = \text{FT}$)
unfolding *is-conj-with-TF-def* **apply** (*rule iffI*)
apply (*induction FNot* φ *rule: grouped-by.induct*)
apply *simp*
apply (*cases* φ ; *simp*)
apply *auto*
done

lemma
shows *no-T-F-FF[simp]*: $\neg \text{no-T-F FF}$ **and**
no-T-F-FT[simp]: $\neg \text{no-T-F FT}$
unfolding *no-T-F-def all-subformula-st-def* **by** *auto*

lemma *grouped-by-CAnd-FAnd*:
grouped-by CAnd (*FAnd* φ_1 φ_2) \longleftrightarrow *grouped-by CAnd* $\varphi_1 \wedge$ *grouped-by CAnd* φ_2
apply (*rule iffI*)

apply (*induction FAnd $\varphi 1$ $\varphi 2$ rule: grouped-by.induct*)
using *connected-is-group*[of *CAnd $\varphi 1$ $\varphi 2$*] **by** *auto*

lemma *grouped-by-COr-FOr*:
grouped-by COr (FOr $\varphi 1$ $\varphi 2$) \longleftrightarrow grouped-by COr $\varphi 1 \wedge$ grouped-by COr $\varphi 2$
apply (*rule iffI*)
apply (*induction FOr $\varphi 1$ $\varphi 2$ rule: grouped-by.induct*)
using *connected-is-group*[of *COr $\varphi 1$ $\varphi 2$*] **by** *auto*

lemma *grouped-by-COr-FAnd[simp]*: \neg *grouped-by COr (FAnd $\varphi 1$ $\varphi 2$)*
apply *clarify*
apply (*induction FAnd $\varphi 1$ $\varphi 2$ rule: grouped-by.induct*)
apply *auto*
done

lemma *grouped-by-COr-FEq[simp]*: \neg *grouped-by COr (FEq $\varphi 1$ $\varphi 2$)*
apply *clarify*
apply (*induction FEq $\varphi 1$ $\varphi 2$ rule: grouped-by.induct*)
apply *auto*
done

lemma [*simp*]: \neg *grouped-by COr (FImp φ ψ)*
apply *clarify*
by (*induction FImp φ ψ rule: grouped-by.induct*) *simp-all*

lemma [*simp*]: \neg *is-conj-with-TF (FImp φ ψ)*
unfolding *is-conj-with-TF-def* **apply** *clarify*
by (*induction FImp φ ψ rule: super-grouped-by.induct*) *simp-all*

lemma [*simp*]: \neg *grouped-by COr (FEq φ ψ)*
apply *clarify*
by (*induction FEq φ ψ rule: grouped-by.induct*) *simp-all*

lemma [*simp*]: \neg *is-conj-with-TF (FEq φ ψ)*
unfolding *is-conj-with-TF-def* **apply** *clarify*
by (*induction FEq φ ψ rule: super-grouped-by.induct*) *simp-all*

lemma *is-conj-with-TF-Fand*:
is-conj-with-TF (FAnd $\varphi 1$ $\varphi 2$) \implies is-conj-with-TF $\varphi 1 \wedge$ is-conj-with-TF $\varphi 2$
unfolding *is-conj-with-TF-def*
apply (*induction FAnd $\varphi 1$ $\varphi 2$ rule: super-grouped-by.induct*)
apply (*auto simp: grouped-by-CAnd-FAnd intro: grouped-is-super-grouped*)[]
apply *auto*[]
done

lemma *is-conj-with-TF-FOr*:
is-conj-with-TF (FOr $\varphi 1$ $\varphi 2$) \implies grouped-by COr $\varphi 1 \wedge$ grouped-by COr $\varphi 2$
unfolding *is-conj-with-TF-def*
apply (*induction FOr $\varphi 1$ $\varphi 2$ rule: super-grouped-by.induct*)
apply (*auto simp: grouped-by-COr-FOr*)[]
apply *auto*[]
done

lemma *grouped-by-COr-mset-of-formula*:
grouped-by COr $\varphi \implies$ mset-of-formula $\varphi =$ (if $\varphi = FT$ then $\{\}$ else $\{\text{mset-of-conj } \varphi\})$

by (induction φ) (auto simp add: grouped-by-COr-FNot)

When a formula is in CNF form, then there is equisatisfiability between the multiset version and the CNF form. Remark that the definition for the entailment are slightly different: $op \models$ uses a function assigning *True* or *False*, while $op \models s$ uses a set where being in the list means entailment of a literal.

theorem

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

assumes *is-cnf* φ

shows $eval\ A\ \varphi \longleftrightarrow Partial\text{-}Clausal\text{-}Logic.true\text{-}class\ (\{Pos\ v|v. A\ v\} \cup \{Neg\ v|v. \neg A\ v\})$
(*mset-of-formula* φ)

using *assms*

proof (induction φ)

case *FF*

then show ?case by auto

next

case *FT*

then show ?case by auto

next

case (*FVar* v)

then show ?case by auto

next

case (*FAnd* $\varphi\ \psi$)

then show ?case

unfolding *is-cnf-def* by (auto simp: *is-conj-with-TF-FNot* dest: *is-conj-with-TF-Fand*
dest!:*is-conj-with-TF-FOr*)

next

case (*FOr* $\varphi\ \psi$)

then have [*simp*]: *mset-of-formula* $\varphi = \{mset\text{-of-conj}\ \varphi\}$ *mset-of-formula* $\psi = \{mset\text{-of-conj}\ \psi\}$
unfolding *is-cnf-def* by (auto dest!:*is-conj-with-TF-FOr* simp: *grouped-by-COr-mset-of-formula*
split: *if-splits*)

have *is-conj-with-TF* φ *is-conj-with-TF* ψ

using *FOr*(3) unfolding *is-cnf-def* no-*T-F-def*

by (*metis* *grouped-is-super-grouped* *is-conj-with-TF-FOr* *is-conj-with-TF-def*)+

then show ?case using *FOr*

unfolding *is-cnf-def* by *simp*

next

case (*FImp* $\varphi\ \psi$)

then show ?case

unfolding *is-cnf-def* by auto

next

case (*FEq* $\varphi\ \psi$)

then show ?case

unfolding *is-cnf-def* by auto

next

case (*FNot* φ)

then show ?case

unfolding *is-cnf-def* by (auto simp: *is-conj-with-TF-FNot*)

qed

end

theory *Prop-Resolution*

imports *Partial-Clausal-Logic* *List-More* *Wellfounded-More*

begin

Chapter 4

Resolution-based techniques

This chapter contains the formalisation of resolution and superposition.

4.1 Resolution

4.1.1 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

4.1.2 Unconstrained Resolution

type-synonym *'v uncon-state* = *'v clauses*
inductive *uncon-res* :: *'v uncon-state* \Rightarrow *'v uncon-state* \Rightarrow *bool* **where**
resolution:
 $\{\#Pos\ p\# \} + C \in N \implies \{\#Neg\ p\# \} + D \in N \implies (\{\#Pos\ p\# \} + C, \{\#Neg\ p\# \} + D) \notin$
already-used
 $\implies \text{uncon-res } (N) (N \cup \{C + D\}) \mid$
factoring: $\{\#L\# \} + \{\#L\# \} + C \in N \implies \text{uncon-res } N (N \cup \{C + \{\#L\# \}\})$

lemma *uncon-res-increasing*:
assumes *uncon-res* $S\ S'$ **and** $\psi \in S$
shows $\psi \in S'$
using *assms* **by** (*induct rule: uncon-res.induct*) *auto*

lemma *rtranclp-uncon-inference-increasing*:
assumes *rtranclp uncon-res* $S\ S'$ **and** $\psi \in S$
shows $\psi \in S'$
using *assms* **by** (*induct rule: rtranclp-induct*) (*auto simp add: uncon-res-increasing*)

Subsumption

definition *subsumes* :: *'a literal multiset* \Rightarrow *'a literal multiset* \Rightarrow *bool* **where**
subsumes $\chi\ \chi' \longleftrightarrow$
 $(\forall I. \text{total-over-m } I\ \{\chi'\} \longrightarrow \text{total-over-m } I\ \{\chi\})$
 $\wedge (\forall I. \text{total-over-m } I\ \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models \chi')$

lemma *subsumes-refl[simp]*:
subsumes $\chi\ \chi$
unfolding *subsumes-def* **by** *auto*

lemma *subsumes-subsumption*:
assumes *subsumes* $D\ \chi$
and $C \subset\# D$ **and** $\neg \text{tautology } \chi$
shows *subsumes* $C\ \chi$ **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* $(C + \{\#Pos\ P\# \} + \{\#Neg\ P\# \})\ \chi$
shows *tautology* χ
using *assms* **unfolding** *subsumes-def* **by** (*simp add: tautology-def*)

4.1.3 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:

$\{\#Pos\ p\#\} + C \in N \implies \{\#Neg\ p\#\} + D \in N \implies (\{\#Pos\ p\#\} + C, \{\#Neg\ p\#\} + D) \notin$
already-used
 $\implies \text{inference-clause } (N, \text{already-used}) (C + D, \text{already-used} \cup \{(\{\#Pos\ p\#\} + C, \{\#Neg\ p\#\} + D)\}) \mid$
factoring: $\{\#L\#\} + \{\#L\#\} + C \in N \implies \text{inference-clause } (N, \text{already-used}) (C + \{\#L\#\}, \text{already-used})$

inductive *inference* :: 'v state \Rightarrow 'v state \Rightarrow bool **where**

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

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* (*fst* *S* \cup {*fst* *S'*}, *snd* *S'*)
using *assms* **apply** (*induct* rule: *inference-clause.induct*)
by *fastforce*+

lemma *inference-preserves-already-used-inv:*

assumes *inference* *S S'*
and *already-used-inv* *S*
shows *already-used-inv* *S'*
using *assms*

proof (*induct* rule: *inference.induct*)

case (*inference-step* *S* *clause* *already-used*)

then show ?*case*

using *inference-clause-preserves-already-used-inv*[of *S* (*clause*, *already-used*)] **by** *simp*

qed

lemma *rtranclp-inference-preserves-already-used-inv:*

assumes *rtranclp inference* *S S'*
and *already-used-inv* *S*
shows *already-used-inv* *S'*
using *assms* **apply** (*induct* rule: *rtranclp-induct*, *simp*)
using *inference-preserves-already-used-inv* **unfolding** *tautology-def* **by** *fast*

lemma *subsumes-condensation:*

assumes *subsumes* (*C* + {*#L*##} + {*#L*##}) *D*
shows *subsumes* (*C* + {*#L*##}) *D*
using *assms* **unfolding** *subsumes-def* **by** *simp*

lemma *simplify-preserves-already-used-inv:*

assumes *simplify* *N N'*
and *already-used-inv* (*N*, *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 set and P
  have  $(\exists x \in \text{Set.remove } a \ A. P \ x) \longleftrightarrow (\exists x \in A. x \neq a \wedge P \ x)$  by auto
} note ex-member-remove = this
{
  fix a a0 :: 'v clause and A :: 'v clauses and y
  assume  $a \in A$  and  $a0 \subset\# a$ 
  then have  $(\exists x \in A. \text{subsumes } x \ y) \longleftrightarrow (\text{subsumes } a \ y \vee (\exists x \in A. x \neq a \wedge \text{subsumes } x \ y))$ 
    by auto
} note tt2 = this
case (subsumption A B) note A = this(1) and AB = this(2) and B = this(3) and inv = this(4)
show ?case
proof (standard, standard)
  fix x a b
  assume  $x: x \in \text{snd } (N - \{B\}, \text{already-used})$  and [simp]:  $x = (a, b)$ 
  obtain p where  $p: \text{Pos } p \in\# a \wedge \text{Neg } p \in\# b$  and
     $q: (\exists \chi \in N. \text{subsumes } \chi (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
     $\vee \text{tautology } (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\}))$ 
  using inv x by fastforce
  consider (taut)  $\text{tautology } (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})) \mid$ 
     $(\chi) \chi$  where  $\chi \in N$   $\text{subsumes } \chi (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\}))$ 
     $\neg \text{tautology } (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\}))$ 
  using q by auto
  then show
     $\exists p. \text{Pos } p \in\# a \wedge \text{Neg } p \in\# b$ 
     $\wedge ((\exists \chi \in \text{fst } (N - \{B\}, \text{already-used}). \text{subsumes } \chi (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
     $\vee \text{tautology } (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
  proof cases
    case taut
    then show ?thesis using p by auto
  next
    case  $\chi$  note H = this
    show ?thesis using p A AB B subsumes-subsumption[OF - AB H(3)] H(1,2) by auto
  qed
qed
next
case (tautology-deletion C P)
then show ?case apply clarify
proof -
  fix a b
  assume  $C + \{\# \text{Pos } P\} + \{\# \text{Neg } P\} \in N$ 
  assume already-used-inv (N, already-used)
  and  $(a, b) \in \text{snd } (N - \{C + \{\# \text{Pos } P\} + \{\# \text{Neg } P\}\}, \text{already-used})$ 
  then obtain p where
     $\text{Pos } p \in\# a \wedge \text{Neg } p \in\# b \wedge$ 
     $((\exists \chi \in \text{fst } (N \cup \{C + \{\# \text{Pos } P\} + \{\# \text{Neg } P\}\}, \text{already-used}).$ 
     $\text{subsumes } \chi (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
     $\vee \text{tautology } (a - \{\# \text{Pos } p\} + (b - \{\# \text{Neg } p\})))$ 
  by fastforce
  moreover have  $\text{tautology } (C + \{\# \text{Pos } P\} + \{\# \text{Neg } P\})$  by auto
  ultimately show
     $\exists p. \text{Pos } p \in\# a \wedge \text{Neg } p \in\# b$ 
     $\wedge ((\exists \chi \in \text{fst } (N - \{C + \{\# \text{Pos } P\} + \{\# \text{Neg } P\}\}, \text{already-used}).$ 

```

$$\text{subsumes } \chi (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$$

$$\vee \text{tautology } (a - \{\#Pos\ p\# \} + (b - \{\#Neg\ p\# \})))$$
by (*metis* (*no-types*) *Diff-iff* *Un-insert-right* *empty-iff* *fst-conv* *insertE* *subsumes-tautology* *sup-bot.right-neutral*)

qed

qed

lemma

factoring-satisfiable: $I \models \{\#L\# \} + \{\#L\# \} + C \longleftrightarrow I \models \{\#L\# \} + C$ **and**
resolution-satisfiable:
consistent-interp $I \implies I \models \{\#Pos\ p\# \} + C \implies I \models \{\#Neg\ p\# \} + D \implies I \models C + D$ **and**
factoring-same-vars: $\text{atms-of } (\{\#L\# \} + \{\#L\# \} + C) = \text{atms-of } (\{\#L\# \} + C)$
unfolding *true-cls-def* *consistent-interp-def* **by** (*fastforce* *split*: *if-split-asm*)**+**

lemma *inference-increasing*:

assumes *inference* $S\ S'$ **and** $\psi \in \text{fst } S$
shows $\psi \in \text{fst } S'$
using *assms* **by** (*induct* *rule*: *inference.induct*, *auto*)

lemma *rtranclp-inference-increasing*:

assumes *rtranclp inference* $S\ S'$ **and** $\psi \in \text{fst } S$
shows $\psi \in \text{fst } S'$
using *assms* **by** (*induct* *rule*: *rtranclp-induct*, *auto* *simp* *add*: *inference-increasing*)

lemma *inference-clause-already-used-increasing*:

assumes *inference-clause* $S\ S'$
shows $\text{snd } S \subseteq \text{snd } S'$
using *assms* **by** (*induct* *rule*: *inference-clause.induct*, *auto*)

lemma *inference-already-used-increasing*:

assumes *inference* $S\ S'$
shows $\text{snd } S \subseteq \text{snd } S'$
using *assms* **apply** (*induct* *rule*: *inference.induct*)
using *inference-clause-already-used-increasing* **by** *fastforce*

lemma *inference-clause-preserves-un-sat*:

fixes $N\ N' :: 'v\ \text{clauses}$
assumes *inference-clause* $T\ T'$
and *total-over-m* $I\ (\text{fst } T)$
and *consistent*: *consistent-interp* I
shows $I \models_s \text{fst } T \longleftrightarrow I \models_s \text{fst } T \cup \{\text{fst } T'\}$
using *assms* **apply** (*induct* *rule*: *inference-clause.induct*)
unfolding *consistent-interp-def* *true-clss-def* **by** *auto* *force***+**

lemma *inference-preserves-un-sat*:

fixes $N\ N' :: 'v\ \text{clauses}$
assumes *inference* $T\ T'$
and *total-over-m* $I\ (\text{fst } T)$
and *consistent*: *consistent-interp* I
shows $I \models_s \text{fst } T \longleftrightarrow I \models_s \text{fst } T'$
using *assms* **apply** (*induct* *rule*: *inference.induct*)
using *inference-clause-preserves-un-sat* **by** *fastforce*

lemma *inference-clause-preserves-atms-of-ms*:
assumes *inference-clause* $S S'$
shows $\text{atms-of-ms } (\text{fst } (S \cup \{\text{fst } S'\}, \text{snd } S')) \subseteq \text{atms-of-ms } (\text{fst } S)$
using *assms* **apply** (*induct rule: inference-clause.induct*)
apply *auto*
apply (*metis Set.set-insert UnCI atms-of-ms-insert atms-of-plus*)
apply (*metis Set.set-insert UnCI atms-of-ms-insert atms-of-plus*)
apply (*simp add: in-m-in-literals union-assoc*)
unfolding *atms-of-ms-def* **using** *assms* **by** *fastforce*

lemma *inference-preserves-atms-of-ms*:
fixes $N N' :: 'v \text{ clauses}$
assumes *inference* $T T'$
shows $\text{atms-of-ms } (\text{fst } T') \subseteq \text{atms-of-ms } (\text{fst } T)$
using *assms* **apply** (*induct rule: inference.induct*)
using *inference-clause-preserves-atms-of-ms* **by** *fastforce*

lemma *inference-preserves-total*:
fixes $N N' :: 'v \text{ clauses}$
assumes *inference* $(N, \text{already-used}) (N', \text{already-used'})$
shows $\text{total-over-m } I N \implies \text{total-over-m } I N'$
using *assms* *inference-preserves-atms-of-ms* **unfolding** *total-over-m-def total-over-set-def*
by *fastforce*

lemma *rtranclp-inference-preserves-total*:
assumes *rtranclp inference* $T T'$
shows $\text{total-over-m } I (\text{fst } T) \implies \text{total-over-m } I (\text{fst } T')$
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 $\text{total-over-m } I (\text{fst } N)$
and *consistent: consistent-interp* I
shows $I \models_s \text{fst } N \longleftrightarrow I \models_s \text{fst } N'$
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* $(\text{fst } \psi)$
shows *finite* $(\text{fst } \psi')$
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* $(\text{snd } \psi)$
shows *finite* $(\text{snd } \psi')$
using *assms* **by** (*induct rule: inference-clause.induct, auto*)

lemma *inference-preserves-finite-snd*:
assumes *inference* $\psi \psi'$ **and** *finite* $(\text{snd } \psi)$
shows *finite* $(\text{snd } \psi')$
using *assms* *inference-clause-preserves-finite-snd* **by** (*induct rule: inference.induct, fastforce*)

```

lemma rtrancplp-inference-preserves-finite:
  assumes rtrancplp inference  $\psi$   $\psi'$  and finite (fst  $\psi$ )
  shows finite (fst  $\psi'$ )
  using assms by (induct rule: rtrancplp-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: image-iff)
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:  $I \models ?\psi'$  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  $I \models \psi$  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]:

```

( $\bigwedge xs:: 'v \text{ sem-tree. } (\bigwedge ys:: 'v \text{ sem-tree. } \text{sem-tree-size } ys < \text{sem-tree-size } xs \implies P \ ys) \implies P \ xs$ )
 $\implies P \ xs$ 
by (fact Nat.measure-induct-rule)

```

fun partial-interps :: 'v sem-tree \Rightarrow 'v interp \Rightarrow 'v clauses \Rightarrow bool **where**

```

partial-interps Leaf I  $\psi$  = ( $\exists \chi. \neg I \models \chi \wedge \chi \in \psi \wedge \text{total-over-m } I \ \{\chi\}$ ) |
partial-interps (Node v ag ad) I  $\psi \longleftrightarrow$ 
  (partial-interps ag (I  $\cup \{\text{Pos } v\}$ )  $\psi \wedge \text{partial-interps } ad \ (I \cup \{\text{Neg } v\}) \ \psi$ )

```

lemma simplify-preserve-partial-leaf:

```

simplify N N'  $\implies$  partial-interps Leaf I N  $\implies$  partial-interps Leaf I N'
apply (induct rule: simplify.induct)

```

```

    using union-lcomm apply auto[1]
    apply (simp, metis atms-of-plus total-over-set-union true-cls-union)
apply simp
by (metis atms-of-ms-singleton mset-le-exists-conv subset-mset-def true-cls-mono-leD
    total-over-m-def total-over-m-sum)

```

```

lemma simplify-preserve-partial-tree:
  assumes simplify  $N\ N'$ 
  and partial-interps  $t\ I\ N$ 
  shows partial-interps  $t\ I\ N'$ 
  using assms apply (induct  $t$  arbitrary:  $I$ , simp)
  using simplify-preserve-partial-leaf by metis

```

```

lemma inference-preserve-partial-tree:
  assumes inference  $S\ S'$ 
  and partial-interps  $t\ I\ (\text{fst } S)$ 
  shows partial-interps  $t\ I\ (\text{fst } S')$ 
  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  $t\ I\ (\text{fst } N)$ 
  shows partial-interps  $t\ I\ (\text{fst } N')$ 
  using assms apply (induct rule: rtranclp-induct, auto)
  using inference-preserve-partial-tree by force

```

```

function build-sem-tree :: 'v :: linorder set  $\Rightarrow$  'v clauses  $\Rightarrow$  'v sem-tree where
  build-sem-tree atms  $\psi$  =
    (if atms = {}  $\vee$   $\neg$  finite atms
     then Leaf
     else Node (Min atms) (build-sem-tree (Set.remove (Min atms) atms)  $\psi$ )
      (build-sem-tree (Set.remove (Min atms) atms)  $\psi$ ))
by auto
termination
  apply (relation measure ( $\lambda(A, -). \text{card } A$ ), simp-all)
  apply (metis Min-in card-Diff1-less remove-def)+
done
declare build-sem-tree.induct[case-names tree]

```

```

lemma unsatisfiable-empty[simp]:
   $\neg$ unsatisfiable {}
  unfolding satisfiable-def apply auto
  using consistent-interp-def unfolding total-over-m-def total-over-set-def atms-of-ms-def by blast

```

```

lemma partial-interps-build-sem-tree-atms-general:
  fixes  $\psi :: 'v :: linorder$  clauses and  $p :: 'v$  literal list
  assumes unsat: unsatisfiable  $\psi$  and finite  $\psi$  and consistent-interp  $I$ 
  and finite atms
  and atms-of-ms  $\psi$  = atms  $\cup$  atms-of-s  $I$  and atms  $\cap$  atms-of-s  $I$  = {}
  shows partial-interps (build-sem-tree atms  $\psi$ )  $I\ \psi$ 
  using assms

```



```

proof (induct arbitrary: I rule: build-sem-tree.induct)
  case (1 atms  $\psi$  Ia) note IH1 = this(1) and IH2 = this(2) and unsat = this(3) and finite = this(4)
  and cons = this(5) and f = this(6) and un = this(7) and disj = this(8)
  {
    assume atms: atms = {}
    then have atmsIa: atms-of-ms  $\psi$  = atms-of-s Ia using un by auto
    then have total-over-m Ia  $\psi$  unfolding total-over-m-def atmsIa by auto
    then have  $\chi$ :  $\exists \chi \in \psi. \neg Ia \models \chi$ 
      using unsat cons unfolding true-clss-def satisfiable-def by auto
    then have build-sem-tree atms  $\psi$  = Leaf using atms by auto
    moreover
      have tot:  $\bigwedge \chi. \chi \in \psi \implies \text{total-over-m } Ia \{ \chi \}$ 
      unfolding total-over-m-def total-over-set-def atms-of-ms-def atms-of-s-def
      using atmsIa atms-of-ms-def by fastforce
    have partial-interps Leaf Ia  $\psi$ 
      using  $\chi$  tot by (auto simp add: total-over-m-def total-over-set-def atms-of-ms-def)

    ultimately have ?case by metis
  }
moreover {
  assume atms: atms  $\neq \{\}$ 
  have build-sem-tree atms  $\psi$  = Node (Min atms) (build-sem-tree (Set.remove (Min atms) atms)  $\psi$ )
    (build-sem-tree (Set.remove (Min atms) atms)  $\psi$ )
    using build-sem-tree.simps[of atms  $\psi$ ] f atms by metis

  have consistent-interp (Ia  $\cup \{Pos (Min\ atms)\}$ ) 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 (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 (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* ψ and *finite*: *finite* ψ
 shows *partial-interps* (*build-sem-tree* (*atms-of-ms* ψ) ψ) $\{\}$ ψ

proof –

have *consistent-interp* $\{\}$ **unfolding** *consistent-interp-def* **by** *auto*
 moreover have *atms-of-ms* $\psi = \text{atms-of-ms } \psi \cup \text{atms-of-s } \{\}$ **unfolding** *atms-of-s-def* **by** *auto*
 moreover have *atms-of-ms* $\psi \cap \text{atms-of-s } \{\} = \{\}$ **unfolding** *atms-of-s-def* **by** *auto*
 moreover have *finite* (*atms-of-ms* ψ) **unfolding** *atms-of-ms-def* **using** *finite* **by** *simp*
 ultimately show *partial-interps* (*build-sem-tree* (*atms-of-ms* ψ) ψ) $\{\}$ ψ
 using *partial-interps-build-sem-tree-atms-general*[*of* $\psi \{\}$ *atms-of-ms* ψ] *assms* **by** *metis*

qed

lemma can-decrease-count:

fixes $\psi'' :: 'v \text{ clauses} \times ('v \text{ clause} \times 'v \text{ clause} \times 'v) \text{ set}$
 assumes *count* $\chi \ L = n$
 and $L \in \# \chi$ and $\chi \in \text{fst } \psi$
 shows $\exists \psi' \chi'. \text{inference}^{**} \psi \psi' \wedge \chi' \in \text{fst } \psi' \wedge (\forall L. L \in \# \chi \longleftrightarrow L \in \# \chi')$
 $\wedge \text{count } \chi' \ L = 1$
 $\wedge (\forall \varphi. \varphi \in \text{fst } \psi \longrightarrow \varphi \in \text{fst } \psi')$
 $\wedge (I \models \chi \longleftrightarrow I \models \chi')$
 $\wedge (\forall I'. \text{total-over-m } I' \{\chi\} \longrightarrow \text{total-over-m } I' \{\chi'\})$

using *assms*

proof (induct n arbitrary: $\chi \psi$)

case 0

then show ?case by (*simp add: not-in-iff[symmetric]*)

next

case (*Suc* $n \chi$)

note $IH = \text{this}(1)$ and $\text{count} = \text{this}(2)$ and $L = \text{this}(3)$ and $\chi = \text{this}(4)$

{

assume $n = 0$

then have *inference*^{**} $\psi \psi$

and $\chi \in \text{fst } \psi$

and $\forall L. (L \in \# \chi) \longleftrightarrow (L \in \# \chi)$

and $\text{count } \chi \ L = (1::\text{nat})$

and $\forall \varphi. \varphi \in \text{fst } \psi \longrightarrow \varphi \in \text{fst } \psi$

by (*auto simp add: count L* χ)

then have ?case by *metis*

}

moreover {

assume $n > 0$

then have $\exists C. \chi = C + \{\#L, L\# \}$

by (*smt L Suc-eq-plus1-left add.left-commute add-diff-cancel-left' add-diff-cancel-right'*
count-greater-zero-iff count-single local.count multi-member-split plus-multiset.rep-eq)

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 $L \chi' : L \in \# ? \chi'$ **by** *auto*

moreover have $\chi' \psi'$: $? \chi' \in \text{fst } ? \psi'$ **by auto**
ultimately obtain ψ'' **and** χ''
where
*inference*** $? \psi' \psi''$ **and**
 α : $\chi'' \in \text{fst } \psi''$ **and**
 $\forall La. (La \in \# ? \chi') \longleftrightarrow (La \in \# \chi'')$ **and**
 β : $\text{count } \chi'' L = (1::\text{nat})$ **and**
 φ' : $\forall \varphi. \varphi \in \text{fst } ? \psi' \longrightarrow \varphi \in \text{fst } \psi''$ **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 $IH[\text{of } ? \chi' ? \psi'] \text{ count' } L\chi' \chi' \psi'$ **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** $\varphi \var'$ **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 $? \text{case}$ **using** $\varphi \var' \alpha \beta$ **by metis**

}
ultimately show $? \text{case}$ **by auto**
qed

lemma *can-decrease-tree-size*:
fixes $\psi :: 'v \text{ state}$ **and** $\text{tree} :: 'v \text{ sem-tree}$
assumes *finite* ($\text{fst } \psi$) **and** *already-used-inv* ψ
and *partial-interps tree I* ($\text{fst } \psi$)
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** $IH = \text{this}(1)$ **and** $\text{finite} = \text{this}(2)$ **and** $\text{a-u-i} = \text{this}(3)$ **and** $\text{part} = \text{this}(4)$

{
assume $\text{sem-tree-size } xs = 0$
then have $? \text{case}$ **using** *part* **by blast**
}

moreover {
assume $\text{sn0}: \text{sem-tree-size } xs > 0$
obtain $ag \text{ ad } v$ **where** $xs: xs = \text{Node } v \text{ ag ad}$ **using** sn0 **by** (*cases xs, auto*)
{
assume $\text{sem-tree-size } ag = 0$ **and** $\text{sem-tree-size } ad = 0$
then have $ag: ag = \text{Leaf}$ **and** $ad: ad = \text{Leaf}$ **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 $\text{Pos}v: \text{Pos } v \notin \# \chi$ **using** χ **unfolding** *true-cls-def true-lit-def* **by auto**
have $\text{Neg}v: \text{Neg } v \notin \# \chi'$ **using** χ' **unfolding** *true-cls-def true-lit-def* **by auto**

```

{
  assume Negχ: Neg v ∉# χ
  have ¬ I ⊨ χ using χ Posv unfolding true-cls-def true-lit-def by auto
  moreover have total-over-m I {χ}
    using Posv Negχ atm-imp-pos-or-neg-lit totχ unfolding total-over-m-def total-over-set-def
    by fastforce
  ultimately have partial-interps Leaf I (fst ψ)
  and sem-tree-size Leaf < sem-tree-size xs
  and inference** ψ ψ
    unfolding xs by (auto simp add: χψ)
}
moreover {
  assume Posχ: Pos v ∉# χ'
  then have Iχ: ¬ I ⊨ χ' using χ' Posv unfolding true-cls-def true-lit-def by auto
  moreover have total-over-m I {χ'}
    using Negv Posχ atm-imp-pos-or-neg-lit totχ' unfolding total-over-m-def total-over-set-def by fastforce
  ultimately have partial-interps Leaf I (fst ψ) and
    sem-tree-size Leaf < sem-tree-size xs and
    inference** ψ ψ
    using χ'ψ Iχ unfolding xs by auto
}
moreover {
  assume neg: Neg v ∈# χ and pos: Pos v ∈# χ'
  then obtain ψ' χ2 where inf: rtrnclp inference ψ ψ' and χ2incl: χ2 ∈ fst ψ'
    and χχ2incl: ∀ L. L ∈# χ ↔ L ∈# χ2
    and countχ2: count χ2 (Neg v) = 1
    and φ: ∀ φ::'v literal multiset. φ ∈ fst ψ → φ ∈ fst ψ'
    and Iχ: I ⊨ χ ↔ I ⊨ χ2
    and tot-impχ: ∀ I'. total-over-m I' {χ} → total-over-m I' {χ2}
    using can-decrease-count[of χ Neg v count χ (Neg v) ψ I] χψ χ'ψ by auto

  have χ' ∈ fst ψ' by (simp add: χ'ψ φ)
  with pos
  obtain ψ'' χ2' where
    inf': inference** ψ' ψ''
    and χ2'-incl: χ2' ∈ fst ψ''
    and χ'χ2'-incl: ∀ L::'v literal. (L ∈# χ') = (L ∈# χ2')
    and countχ2': count χ2' (Pos v) = (1::nat)
    and φ': ∀ φ::'v literal multiset. φ ∈ fst ψ' → φ ∈ fst ψ''
    and Iχ': I ⊨ χ' ↔ I ⊨ χ2'
    and tot-impχ': ∀ I'. total-over-m I' {χ'} → total-over-m I' {χ2'}
    using can-decrease-count[of χ' Pos v count χ' (Pos v) ψ' I] by auto

  obtain C where χ2: χ2 = C + {#Neg v#} and negC: Neg v ∉# C and posC: Pos v ∉# C
  proof -
    have ∧m. Suc 0 - count m (Neg v) = count (χ2 - m) (Neg v)
      by (simp add: countχ2)
    then show ?thesis
      using that by (metis (no-types) One-nat-def Posv Suc-inject Suc-pred χχ2-incl
        count-diff count-single insert-DiffM2 mem-Collect-eq multi-member-skip neg
        not-gr0 set-mset-def union-commute)
  qed

  obtain C' where
    χ2': χ2' = C' + {#Pos v#} and

```

```

posC': Pos v  $\notin$  # C' and
negC': Neg v  $\notin$  # C'
proof -
  assume a1:  $\bigwedge C'. \llbracket \chi^{2'} = C' + \{\#Pos\ v\#\}; Pos\ v \notin \# C'; Neg\ v \notin \# C' \rrbracket \implies thesis$ 
  have f2:  $\bigwedge n. (n::nat) - n = 0$ 
    by simp
  have Neg v  $\notin$  #  $\chi^{2'} - \{\#Pos\ v\#$ 
    using Negv  $\chi' \chi^{2'}\text{-incl}$  by (auto simp: not-in-iff)
  have count  $\{\#Pos\ v\#$  (Pos v) = 1
    by simp
  then show ?thesis
    by (metis  $\chi' \chi^{2'}\text{-incl}$   $\langle Neg\ v \notin \# \chi^{2'} - \{\#Pos\ v\#\} \rangle$  a1 count $\chi^{2'}$  count-diff f2
        insert-DiffM2 less-numeral-extra(3) mem-Collect-eq pos set-mset-def)
qed

have already-used-inv  $\psi'$ 
  using rtranclp-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 rtranclp-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 by auto
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 ( $\{\#Pos\ v\#\} + C', \{\#Neg\ v\#\} + C$ )  $\notin$  snd  $\psi''$ 
  then have inf'': inference  $\psi''$  (fst  $\psi'' \cup \{C + C'\}$ , snd  $\psi'' \cup \{(\chi^{2'}, \chi^2)\}$ )
    using add.commute  $\varphi' \chi^{2'}\text{incl}$   $\langle \chi^{2'} \in \text{fst } \psi'' \rangle$  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'' rtranclp-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: ( $\{\#Pos\ v\#\} + C', \{\#Neg\ v\#\} + C$ )  $\in$  snd  $\psi''$ 
  then have ( $\exists \chi \in \text{fst } \psi''.$  ( $\forall I. \text{total-over-m } I \{C + C'\} \longrightarrow \text{total-over-m } I \{\chi\}$ )
     $\wedge (\forall I. \text{total-over-m } I \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models C' + C)$ )
     $\vee$  tautology ( $C' + C$ )
  proof -
    obtain p where p: Pos p  $\in$  # ( $\{\#Pos\ v\#\} + C'$ ) and
      n: Neg p  $\in$  # ( $\{\#Neg\ v\#\} + C$ ) and
      decomp: ( $\exists \chi \in \text{fst } \psi''.$ 
        ( $\forall I. \text{total-over-m } I \{(\{\#Pos\ v\#\} + C') - \{\#Pos\ p\#\}$ 
           $+ ((\{\#Neg\ v\#\} + C) - \{\#Neg\ p\#\})\}$ 
           $\longrightarrow \text{total-over-m } I \{\chi\}$ )
         $\wedge (\forall I. \text{total-over-m } I \{\chi\} \longrightarrow I \models \chi$ 
           $\longrightarrow I \models (\{\#Pos\ v\#\} + C') - \{\#Pos\ p\#\} + ((\{\#Neg\ v\#\} + C) - \{\#Neg\ p\#\}))$ )

```

```

    )
    ∨ tautology (({#Pos v#} + C') - {#Pos p#} + (({#Neg v#} + C) - {#Neg p#})))
using a by (blast intro: allE[OF a-u-i-ψ''[unfolding subsumes-def Ball-def],
    of ({#Pos v#} + C', {#Neg v#} + C)])
  { assume p ≠ v
    then have Pos p ∈# C' ∧ Neg p ∈# C using p n by force
    then have ?thesis unfolding Bex-def by auto
  }
moreover {
  assume p = v
  then have ?thesis using decomp by (metis add.commute add-diff-cancel-left')
}
ultimately show ?thesis by auto
qed
moreover {
assume ∃χ ∈ fst ψ''. (∀I. total-over-m I {C+C'} → total-over-m I {χ})
  ∧ (∀I. total-over-m I {χ} → I ⊨ χ → I ⊨ C' + C)
then obtain ∅ where ∅: ∅ ∈ fst ψ'' and
  tot-∅-CC': ∀I. total-over-m I {C+C'} → total-over-m I {∅} and
  ∅-inv: ∀I. total-over-m I {∅} → I ⊨ ∅ → I ⊨ C' + C by blast
have partial-interps Leaf I (fst ψ'')
  using tot-∅-CC' ∅ ∅-inv totC totC' (⊢ I ⊨ 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 (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 ¬tautology (C' + C)
  using (⊢ I ⊨ C + C') unfolding add.commute[of C C'] total-over-m-def
  unfolding tautology-def by auto
then have False using tautCC' unfolding tautology-def by auto
}
ultimately have ?case by auto
}
ultimately have ?case by auto
}
ultimately have ?case using part by (metis (no-types) sem-tree-size.simps(1))
}
moreover {
assume size-ag: sem-tree-size ag > 0
have sem-tree-size ag < sem-tree-size xs unfolding xs by auto
moreover have partial-interps ag (I ∪ {Pos v}) (fst ψ)
  and partad: partial-interps ad (I ∪ {Neg v}) (fst ψ)
  using part partial-interps.simps(2) unfolding xs by metis+
moreover have sem-tree-size ag < sem-tree-size xs → finite (fst ψ) → already-used-inv ψ
  → ( partial-interps ag (I ∪ {Pos v}) (fst ψ) →
    (∃ tree' ψ'. inference** ψ ψ' ∧ partial-interps tree' (I ∪ {Pos v}) (fst ψ')
      ∧ (sem-tree-size tree' < sem-tree-size ag ∨ sem-tree-size ag = 0)))
  using IH by auto
ultimately obtain ψ' :: 'v state and tree' :: 'v sem-tree where
  inf: inference** ψ ψ'
  and part: partial-interps tree' (I ∪ {Pos v}) (fst ψ')
  and size: sem-tree-size tree' < sem-tree-size ag ∨ sem-tree-size ag = 0
  using finite part rtranclp.rtrancl-refl a-u-i 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  $\psi :: 'v :: linorder$  state
assumes
  unsat:  $\neg$ satisfiable (fst  $\psi$ ) and
  finite: finite (fst  $\psi$ ) and
  a-u-v: already-used-inv  $\psi$ 
shows  $\exists \psi'. (inference** \psi\ \psi' \wedge \{\#\} \in fst\ \psi')$ 
proof -
  obtain tree where partial-interps tree {} (fst  $\psi$ )
  using partial-interps-build-sem-tree-atms assms by metis
  then show ?thesis
  using unsat finite a-u-v
  proof (induct tree arbitrary:  $\psi$  rule: sem-tree-size)
    case (bigger tree  $\psi$ ) note H = this
    {
      fix  $\chi$ 
      assume tree: tree = Leaf
      obtain  $\chi$  where  $\chi: \neg \{\} \models \chi$  and tot $\chi$ : total-over-m {} { $\chi$ } and  $\chi\psi$ :  $\chi \in fst\ \psi$ 
      using H unfolding tree by auto
      moreover have { $\#\}$  =  $\chi$ 
      using tot $\chi$  unfolding total-over-m-def total-over-set-def by fastforce
      moreover have inference**  $\psi\ \psi$  by auto
      ultimately have ?case by metis
    }
  }

```

```

moreover {
  fix  $v$   $tree1$   $tree2$ 
  assume  $tree: tree = Node\ v\ tree1\ tree2$ 
  obtain
     $tree'\ \psi'$  where  $inf: inference^{**}\ \psi\ \psi'$  and
     $part': partial\text{-}interp\ tree'\ \{\}$   $(fst\ \psi')$  and
     $decrease: sem\text{-}tree\text{-}size\ tree' < sem\text{-}tree\text{-}size\ tree \vee sem\text{-}tree\text{-}size\ tree = 0$ 
    using  $can\text{-}decrease\text{-}tree\text{-}size[of\ \psi]\ H(2,4,5)$  unfolding  $tautology\text{-}def$  by  $meson$ 
  have  $sem\text{-}tree\text{-}size\ tree' < sem\text{-}tree\text{-}size\ tree$  using  $decrease$  unfolding  $tree$  by  $auto$ 
  moreover have  $finite\ (fst\ \psi')$  using  $rtranclp\text{-}inference\text{-}preserves\text{-}finite\ inf\ H(4)$  by  $metis$ 
  moreover have  $unsatisfiable\ (fst\ \psi')$ 
    using  $inference\text{-}preserves\text{-}unsat\ inf\ bigger.prem\ s(2)$  by  $blast$ 
  moreover have  $already\text{-}used\text{-}inv\ \psi'$ 
    using  $H(5)\ inf\ rtranclp\text{-}inference\text{-}preserves\text{-}already\text{-}used\text{-}inv[of\ \psi\ \psi']$  by  $auto$ 
  ultimately have  $?case$  using  $inf\ rtranclp\text{-}trans\ part'\ H(1)$  by  $fastforce$ 
}
ultimately show  $?case$  by  $(cases\ tree,\ auto)$ 
qed
qed

```

```

lemma  $inference\text{-}completeness$ :
  fixes  $\psi :: 'v :: linorder\ state$ 
  assumes  $unsat: \neg satisfiable\ (fst\ \psi)$ 
  and  $finite: finite\ (fst\ \psi)$ 
  and  $snd\ \psi = \{\}$ 
  shows  $\exists \psi'. (rtranclp\ inference\ \psi\ \psi' \wedge \{\#\} \in fst\ \psi')$ 
proof –
  have  $already\text{-}used\text{-}inv\ \psi$  unfolding  $assms$  by  $auto$ 
  then show  $?thesis$  using  $assms\ inference\text{-}completeness\text{-}inv$  by  $blast$ 
qed

```

```

lemma  $inference\text{-}soundness$ :
  fixes  $\psi :: 'v :: linorder\ state$ 
  assumes  $rtranclp\ inference\ \psi\ \psi'$  and  $\{\#\} \in fst\ \psi'$ 
  shows  $unsatisfiable\ (fst\ \psi)$ 
  using  $assms$  by  $(meson\ rtranclp\text{-}inference\text{-}preserves\text{-}un\text{-}sat\ satisfiable\text{-}def\ true\text{-}cls\text{-}empty\ true\text{-}clss\text{-}def)$ 

```

```

lemma  $inference\text{-}soundness\text{-}and\text{-}completeness$ :
  fixes  $\psi :: 'v :: linorder\ state$ 
  assumes  $finite: finite\ (fst\ \psi)$ 
  and  $snd\ \psi = \{\}$ 
  shows  $(\exists \psi'. (inference^{**}\ \psi\ \psi' \wedge \{\#\} \in fst\ \psi')) \longleftrightarrow unsatisfiable\ (fst\ \psi)$ 
  using  $assms\ inference\text{-}completeness\ inference\text{-}soundness$  by  $metis$ 

```

4.1.4 Lemma about the simplified state

abbreviation $simplified\ \psi \equiv (no\text{-}step\ simplify\ \psi)$

```

lemma  $simplified\text{-}count$ :
  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 (metis (no-types) add.left-neutral add-diff-cancel-left' count-union diff-diff-add
    diff-single-trivial insert-DiffM mem-Collect-eq multi-member-this not-gr0 set-mset-def)
then have  $\chi'$ :  $? \chi' + \{\#L\# \} + \{\#L\# \} = \chi$ 
  using f1 by (metis diff-diff-add diff-single-eq-union in-diffD)

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  $\chi = \chi' + \{\#Pos \ (atm\text{-of } L)\# \} + \{\#Neg \ (atm\text{-of } L)\# \}$ 
    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  $\sim \text{tautology } \psi$ 
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  $\sim \text{simplified } \{\psi\}$  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:  $\neg \text{simplified } \{\psi - \{\#l\# \}\}$ 
  {
    assume  $l \notin \# \psi$ 
    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 {ψ}] add.commute)
next
case (condensation A L)
have A + {#L#} + {#L#} + {#l#} ∈ {ψ}
  using A condensation.hyps by blast
then have {#L, L#} + (A + {#l#}) ∈ {ψ}
  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 ψ and incl: ψ' ⊆ ψ
  shows simplified ψ'
proof (rule ccontr)
  assume ¬ ?thesis
  then obtain ψ'' where simplify ψ' ψ'' by metis
  then have ∃ l'. simplify ψ l'
  proof (induction rule: simplify.induct)
  case (tautology-deletion A P)
  then show ?thesis using simplify.tautology-deletion[of A P ψ] incl by blast
  next
  case (condensation A L)
  then show ?case using simplify.condensation[of A L ψ] incl by blast
  next
  case (subsumption A B)
  then show ?case using simplify.subsumption[of A ψ B] incl by auto
  qed
  then show False using assms(1) by blast
qed

```

lemma *simplified-in*:

```

  assumes simplified ψ
  and N ∈ ψ
  shows simplified {N}
  using assms by (metis Set.set-insert empty-subsetI in-simplified-simplified insert-mono)

```

lemma *subsumes-imp-formula*:

```

  assumes ψ ≤# φ
  shows {ψ} ⊨p φ
  unfolding true-clss-clf-def apply auto
  using assms true-clf-mono-leD by blast

```

lemma *simplified-imp-distinct-mset-tauto*:

```

  assumes simp: simplified ψ'
  shows distinct-mset-set ψ' and ∀χ ∈ ψ'. ¬tautology χ

```

```

proof –
  show  $\forall \chi \in \psi'. \neg \text{tautology } \chi$ 
    using simp by (auto simp add: simplified-in simplified-not-tautology)

  show distinct-mset-set  $\psi'$ 
    proof (rule ccontr)
      assume  $\neg ?thesis$ 
      then obtain  $\chi$  where  $\chi \in \psi'$  and  $\neg \text{distinct-mset } \chi$  unfolding distinct-mset-set-def by auto
      then obtain  $L$  where  $\text{count } \chi \ L \geq 2$ 
        unfolding distinct-mset-def
        by (meson count-greater-eq-one-iff le-antisym simp simplified-count)
      then show False by (metis Suc-1 'χ ∈ ψ' 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)

```

4.1.5 Resolution and Invariants

```

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

```

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 *trancpl-resolution-always-simplified:*

assumes *trancpl resolution $\psi \psi'$*

shows *simplified (fst ψ')*

using *assms by (induct rule: trancpl.induct, auto simp add: resolution-always-simplified)*

lemma *resolution-atms-of:*

assumes *resolution $\psi \psi'$ and finite (fst ψ)*

shows *atms-of-ms (fst ψ') \subseteq atms-of-ms (fst ψ)*

using *assms apply (induct rule: resolution.induct)*

apply(*simp add: rtrancpl-simplify-atms-of-ms trancpl-into-rtrancpl full1-def*)

by (*metis (no-types, lifting) contra-subsetD fst-conv full-def*

inference-preserves-atms-of-ms rtrancpl-simplify-atms-of-ms subsetI)

lemma *rtrancpl-resolution-atms-of:*

assumes *resolution** $\psi \psi'$ and finite (fst ψ)*

shows *atms-of-ms (fst ψ') \subseteq atms-of-ms (fst ψ)*

using *assms apply (induct rule: rtrancpl-induct)*

using *resolution-atms-of rtrancpl-resolution-finite by blast+*

lemma *resolution-include:*

assumes *res: resolution $\psi \psi'$ and finite: finite (fst ψ)*

shows *fst $\psi' \subseteq$ simple-clss (atms-of-ms (fst ψ))*

proof –

have *finite': finite (fst ψ') using local.finite res resolution-finite by blast*

have *simplified (fst ψ') using res finite' resolution-always-simplified by blast*

then have *fst $\psi' \subseteq$ simple-clss (atms-of-ms (fst ψ'))*

using *simplified-in-simple-clss finite' simplified-imp-distinct-mset-tauto[of fst ψ'] by auto*

moreover have *atms-of-ms (fst ψ') \subseteq atms-of-ms (fst ψ)*

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 *rtrancpl-resolution-include:*

assumes *res: trancpl resolution $\psi \psi'$ and finite: finite (fst ψ)*

shows *fst $\psi' \subseteq$ simple-clss (atms-of-ms (fst ψ))*

using *assms apply (induct rule: trancpl.induct)*

apply (*simp add: resolution-include*)

by (*meson simple-clss-mono order-class.le-trans resolution-include*

rtrancpl-resolution-atms-of rtrancpl-resolution-finite trancpl-into-rtrancpl)

abbreviation *already-used-all-simple*

:: ('a literal multiset \times 'a literal multiset) set \Rightarrow 'a set \Rightarrow bool where

already-used-all-simple already-used vars \equiv

*($\forall (A, B) \in$ already-used. *simplified* $\{A\} \wedge$ *simplified* $\{B\} \wedge$ *atms-of* $A \subseteq$ *vars* \wedge *atms-of* $B \subseteq$ *vars*)*

lemma *already-used-all-simple-vars-incl:*

assumes *vars \subseteq vars'*

shows *already-used-all-simple a vars \implies already-used-all-simple a vars'*

using *assms by fast*

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

assumes *inference-clause $S S'$*

and *already-used-all-simple (snd S) vars*

```

and simplified (fst S)
and atms-of-ms (fst S)  $\subseteq$  vars
shows already-used-all-simple (snd (fst S  $\cup$  {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 = this
show ?case apply clarify
proof -
fix A B v
assume (A, B)  $\in$  snd (fst (N, already-used))
 $\cup$  {fst (C + D, already-used  $\cup$  {({#Pos P#} + C, {#Neg P#} + D))},
snd (C + D, already-used  $\cup$  {({#Pos P#} + C, {#Neg P#} + D))})
then have (A, B)  $\in$  already-used  $\vee$  (A, B) = ({#Pos P#} + C, {#Neg P#} + D) by auto
moreover {
assume (A, B)  $\in$  already-used
then have simplified {A}  $\wedge$  simplified {B}  $\wedge$  atms-of A  $\subseteq$  vars  $\wedge$  atms-of B  $\subseteq$  vars
using H(4) by auto
}
moreover {
assume eq: (A, B) = ({#Pos P#} + C, {#Neg P#} + D)
then have simplified {A} using simplified-in H(1,5) by auto
moreover have simplified {B} using eq simplified-in H(2,5) by auto
moreover have atms-of A  $\subseteq$  atms-of-ms N
using eq H(1)
using atms-of-atms-of-ms-mono[of A N] by auto
moreover have atms-of B  $\subseteq$  atms-of-ms N
using eq H(2) atms-of-atms-of-ms-mono[of B N] by auto
ultimately have simplified {A}  $\wedge$  simplified {B}  $\wedge$  atms-of A  $\subseteq$  vars  $\wedge$  atms-of B  $\subseteq$  vars
using H(6) by auto
}
ultimately show simplified {A}  $\wedge$  simplified {B}  $\wedge$  atms-of A  $\subseteq$  vars  $\wedge$  atms-of B  $\subseteq$  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 atms-of-ms (fst S)  $\subseteq$  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 atms-of-ms (fst S)  $\subseteq$  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, already-used)] by simp
qed

lemma rtrancplp-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: rtrancplp-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 rtrancplp-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 trancplpD)
  by (metis inference-simplified-already-used-subset fst-conv snd-conv)

lemma trancplp-resolution-simplified-already-used-subset:
  assumes trancplp resolution S S'

```

and *simplified* (*fst* *S*)
shows *snd* *S* \subset *snd* *S'*
using *assms* **apply** (*induct* rule: *trancp.induct*)
using *resolution-simplified-already-used-subset* **apply** *metis*
by (*meson* *trancp-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 *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 *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 *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 *simple-clss vars* \times *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 *var* \subseteq *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 literal multiset \times 'a literal multiset) set **and** *vars* :: 'a 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* $\psi \equiv$ *card* (*already-used-top vars* $- \psi$)

lemma *resolution-card-simple-decreasing*:

assumes *res*: *resolution* ψ ψ'
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 $\text{atms-of-ms } (\text{fst } \psi) \subseteq \text{vars}$
shows $\text{card-simple vars } (\text{snd } \psi') < \text{card-simple vars } (\text{snd } \psi)$
proof –
let $?vars = \text{vars}$
let $?top = \text{simple-clss } ?vars \times \text{simple-clss } ?vars$
have 1: $\text{card-simple vars } (\text{snd } \psi) = \text{card } ?top - \text{card } (\text{snd } \psi)$
using $\text{card-Diff-subset finite-snd already-used-all-simple-in-already-used-top}[OF \text{ a-u-s}]$
finite-v by metis
have $\text{a-u-s': already-used-all-simple } (\text{snd } \psi') \text{ vars}$
using $\text{already-used-all-simple-inv res a-u-s assms}(7) \text{ by blast}$
have $f: \text{finite } (\text{snd } \psi') \text{ using already-used-all-simple-finite a-u-s' finite-v by auto}$
have 2: $\text{card-simple vars } (\text{snd } \psi') = \text{card } ?top - \text{card } (\text{snd } \psi')$
using $\text{card-Diff-subset}[OF f] \text{ already-used-all-simple-in-already-used-top}[OF \text{ a-u-s' finite-v}]$
by auto
have $\text{card } (\text{already-used-top vars}) \geq \text{card } (\text{snd } \psi')$
using $\text{already-used-all-simple-in-already-used-top}[OF \text{ a-u-s' finite-v}]$
 $\text{card-mono}[of \text{ already-used-top vars snd } \psi'] \text{ already-used-top-finite}[OF \text{ finite-v}] \text{ by metis}$
then show $?thesis$
using $\text{psubset-card-mono}[OF f \text{ resolution-simplified-already-used-subset}[OF \text{ res simp}]]$
unfolding 1 2 **by** linarith
qed

lemma $\text{trancpl-resolution-card-simple-decreasing}$:

assumes $\text{trancpl resolution } \psi \psi' \text{ and finite-fst: finite } (\text{fst } \psi)$
and $\text{already-used-all-simple } (\text{snd } \psi) \text{ vars}$
and $\text{atms-of-ms } (\text{fst } \psi) \subseteq \text{vars}$
and $\text{finite-v: finite vars}$
and $\text{finite-snd: finite } (\text{snd } \psi)$
and $\text{simplified } (\text{fst } \psi)$
shows $\text{card-simple vars } (\text{snd } \psi') < \text{card-simple vars } (\text{snd } \psi)$
using assms
proof ($\text{induct rule: trancpl-induct}$)
case ($\text{base } \psi'$)
then show $?case \text{ by } (\text{simp add: resolution-card-simple-decreasing})$
next
case ($\text{step } \psi' \psi''$) **note** $\text{res} = \text{this}(1) \text{ and } \text{res}' = \text{this}(2) \text{ and } \text{a-u-s} = \text{this}(5) \text{ and}$
 $\text{atms} = \text{this}(6) \text{ and } \text{f-v} = \text{this}(7) \text{ and } \text{f-fst} = \text{this}(4) \text{ and } H = \text{this}$
then have $\text{card-simple vars } (\text{snd } \psi') < \text{card-simple vars } (\text{snd } \psi) \text{ by auto}$
moreover have $\text{a-u-s': already-used-all-simple } (\text{snd } \psi') \text{ vars}$
using $\text{rtrancpl-already-used-all-simple-inv}[OF \text{ trancpl-into-rtrancpl}[OF \text{ res}] \text{ a-u-s atms f-fst}]$.
have $\text{finite } (\text{fst } \psi')$
by ($\text{meson finite-fst res rtrancpl-resolution-finite trancpl-into-rtrancpl}$)
moreover have $\text{finite } (\text{snd } \psi') \text{ using already-used-all-simple-finite}[OF \text{ a-u-s' f-v}]$.
moreover have $\text{simplified } (\text{fst } \psi') \text{ using res trancpl-resolution-always-simplified by blast}$
moreover have $\text{atms-of-ms } (\text{fst } \psi') \subseteq \text{vars}$
by ($\text{meson atms f-fst order.trans res rtrancpl-resolution-atms-of trancpl-into-rtrancpl}$)
ultimately show $?case$
using $\text{resolution-card-simple-decreasing}[OF \text{ res' a-u-s' f-v}] \text{ f-v}$
 $\text{less-trans}[of \text{ card-simple vars } (\text{snd } \psi'') \text{ card-simple vars } (\text{snd } \psi')]$
 $\text{card-simple vars } (\text{snd } \psi)]$
by blast
qed

lemma $\text{trancpl-resolution-card-simple-decreasing-2}$:

assumes *trnclp resolution* $\psi \psi'$
and *finite-fst*: *finite* (*fst* ψ)
and *empty-snd*: *snd* $\psi = \{\}$
and *simplified* (*fst* ψ)
shows *card-simple* (*atms-of-ms* (*fst* ψ)) (*snd* ψ') < *card-simple* (*atms-of-ms* (*fst* ψ)) (*snd* ψ)
proof –
let *?vars* = *atms-of-ms* (*fst* ψ)
have *already-used-all-simple* (*snd* ψ) *?vars* **unfolding** *empty-snd* **by** *auto*
moreover **have** *atms-of-ms* (*fst* ψ) \subseteq *?vars* **by** *auto*
moreover **have** *finite-v*: *finite* *?vars* **using** *finite-fst* **by** *auto*
moreover **have** *finite-snd*: *finite* (*snd* ψ) **unfolding** *empty-snd* **by** *auto*
ultimately show *?thesis*
using *assms(1,2,4)* *trnclp-resolution-card-simple-decreasing[of $\psi \psi'$]* **by** *presburger*
qed

well-foundness if the relation

lemma *wf-simplified-resolution*:

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

lemma *wf-simplified-resolution'*:

assumes *f-vars*: *finite vars*
shows *wf* $\{(y:: 'v:: \text{linorder state}, x). (\text{atms-of-ms } (\text{fst } x) \subseteq \text{vars} \wedge \neg \text{simplified } (\text{fst } x) \wedge \text{finite } (\text{snd } x) \wedge \text{finite } (\text{fst } x) \wedge \text{already-used-all-simple } (\text{snd } x) \text{ vars}) \wedge \text{resolution } x y\}$
unfolding *wf-def*
apply (*simp add*: *resolution-always-simplified*)
by (*metis* (*mono-tags*, *hide-lams*) *fst-conv* *resolution-always-simplified*)

lemma *wf-resolution*:
assumes *f-vars*: *finite vars*
shows $wf \{ (y: 'v:: linorder\ state, x). (atms-of-ms\ (fst\ x) \subseteq vars \wedge simplified\ (fst\ x) \wedge finite\ (snd\ x) \wedge finite\ (fst\ x) \wedge already-used-all-simple\ (snd\ x)\ vars) \wedge resolution\ x\ y \}$
 $\cup \{ (y, x). (atms-of-ms\ (fst\ x) \subseteq vars \wedge \neg simplified\ (fst\ x) \wedge finite\ (snd\ x) \wedge finite\ (fst\ x) \wedge already-used-all-simple\ (snd\ x)\ vars) \wedge resolution\ x\ y \}$ **(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* ψ ψ'
shows *satisfiable* $\psi' \longrightarrow$ *satisfiable* ψ
using *assms* *rtanclp-simplify-preserves-unsat*[*of* ψ ψ'] *tranclp-into-rtranclp*
unfolding *full1-def* **by** *metis*

lemma *full-simplify-preserves-unsat*:
assumes *full simplify* ψ ψ'
shows *satisfiable* $\psi' \longrightarrow$ *satisfiable* ψ
using *assms* *rtanclp-simplify-preserves-unsat*[*of* ψ ψ'] **unfolding** *full-def* **by** *metis*

lemma *resolution-preserves-unsat*:
assumes *resolution* ψ ψ'
shows *satisfiable* (*fst* ψ') \longrightarrow *satisfiable* (*fst* ψ)
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*** ψ ψ'
shows *satisfiable* (*fst* ψ') \longrightarrow *satisfiable* (*fst* ψ)
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 φ L | φ 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

definition *sum-count-ge-2* :: *'a multiset set \Rightarrow nat (Ξ) 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 ($\lambda \varphi. \text{op} + (\text{msetsum } \{\# \text{count } \varphi L \mid L \in \# \varphi. 2 \leq \text{count } \varphi L\}\})) 0 = \text{sum-count-ge-2}$

proof –

show *folding ($\lambda \varphi. \text{op} + (\text{msetsum } (\text{image-mset } (\text{count } \varphi) \{\# L \in \# \varphi. 2 \leq \text{count } \varphi L\}\}))$*
by *standard auto*

then interpret *sum-count-ge-2*:

folding ($\lambda \varphi. \text{op} + (\text{msetsum } \{\# \text{count } \varphi L \mid L \in \# \varphi. 2 \leq \text{count } \varphi L\}\})) 0$.

show *folding.F ($\lambda \varphi. \text{op} + (\text{msetsum } (\text{image-mset } (\text{count } \varphi) \{\# L \in \# \varphi. 2 \leq \text{count } \varphi L\}\})) 0$*
 $= \text{sum-count-ge-2}$ **by** (*auto simp add: sum-count-ge-2-def*)

qed

lemma *finite-incl-le-setsum*:
finite ($B :: 'a$ multiset set) $\implies A \subseteq B \implies \Xi A \leq \Xi B$
proof (*induction arbitrary:A rule: finite-induct*)
 case *empty*
 then show *?case* **by** *simp*
next
 case (*insert a F*) **note** *finite = this(1)* **and** *aF = this(2)* **and** *IH = this(3)* **and** *AF = this(4)*
 show *?case*
 proof (*cases a ∈ A*)
 assume $a \notin A$
 then have $A \subseteq F$ **using** *AF* **by** *auto*
 then show *?case* **using** *IH[of A]* **by** (*simp add: aF local.finite*)
next
 assume $aA: a \in A$
 then have $A - \{a\} \subseteq F$ **using** *AF* **by** *auto*
 then have $\Xi (A - \{a\}) \leq \Xi F$ **using** *IH* **by** *blast*
 then show *?case*
 proof –
 obtain $nn :: nat \Rightarrow nat \Rightarrow nat$ **where**
 $\forall x0\ x1. (\exists v2. x0 = x1 + v2) = (x0 = x1 + nn\ x0\ x1)$
 by *moura*
 then have $\Xi F = \Xi (A - \{a\}) + nn\ (\Xi F)\ (\Xi (A - \{a\}))$
 by (*meson* $\langle \Xi (A - \{a\}) \leq \Xi F \rangle$ *le-iff-add*)
 then show *?thesis*
 by (*metis* (*no-types*) *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 $N\ N' \implies \text{finite } N \implies \text{card } N' + \Xi N' < \text{card } N + \Xi N$
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 $\text{card } ?N' < \text{card } N$
 by (*meson card-Diff1-less tautology-deletion.hyps tautology-deletion.premis*)
 moreover have $?N' \subseteq N$ **by** *auto*
 then have $\text{sum-count-ge-2 } ?N' \leq \text{sum-count-ge-2 } N$ **using** *finite-incl-le-setsum[OF fin]* **by** *blast*
 ultimately show *?case* **by** *linarith*
next
 case (*condensation A L*) **note** $AN = \text{this}(1)$ **and** $fin = \text{this}(2)$
 let $?C' = A + \{\#L\#\}$
 let $?C = A + \{\#L\#\} + \{\#L\#\}$
 let $?N' = N - \{?C\} \cup \{?C'\}$
 have $\text{card } ?N' \leq \text{card } N$
 using AN **by** (*metis* (*no-types, lifting*) *Diff-subset Un-empty-right Un-insert-right card.remove card-insert-if card-mono fin finite-Diff order-refl*)
 moreover have $\Xi \{?C'\} < \Xi \{?C\}$
 proof –
 have *mset-decomp*:
 $\{\# L a \in \# A. (L = La \longrightarrow La \in \# A) \wedge (L \neq La \longrightarrow 2 \leq \text{count } A\ La)\#\}$
 $= \{\# L a \in \# A. L \neq La \wedge 2 \leq \text{count } A\ La\#\} +$
 $\{\# L a \in \# A. L = La \wedge \text{Suc } 0 \leq \text{count } A\ L\#\}$
 by (*auto simp: multiset-eq-iff ac-simps*)
 have *mset-decomp2*: $\{\# L a \in \# A. L \neq La \longrightarrow 2 \leq \text{count } A\ La\#\} =$

```

    {# La ∈# A. L ≠ La ∧ 2 ≤ count A La#} + replicate-mset (count A L) L
  by (auto simp: multiset-eq-iff)
show ?thesis
  by (auto simp: mset-decomp mset-decomp2 filter-mset-eq ac-simps)
qed
have  $\Xi \ ?N' < \Xi \ N$ 
proof cases
  assume a1:  $?C' \in N$ 
  then show ?thesis
    proof -
      have f2:  $\bigwedge m \ M. \text{insert } (m::'a \text{ literal multiset}) (M - \{m\}) = M \cup \{m\} \vee m \notin M$ 
        using Un-empty-right insert-Diff by blast
      have f3:  $\bigwedge m \ M \ Ma. \text{insert } (m::'a \text{ literal multiset}) M - \text{insert } m \ Ma = M - \text{insert } m \ Ma$ 
        by simp
      then have f4:  $\bigwedge M \ m. M - \{m::'a \text{ literal multiset}\} = M \cup \{m\} \vee m \in M$ 
        using Diff-insert-absorb Un-empty-right by fastforce
      have f5:  $\text{insert } (A + \{\#L\# \} + \{\#L\# \}) N = N$ 
        using f3 f2 Un-empty-right condensation.hyps insert-iff by fastforce
      have  $\bigwedge m \ M. \text{insert } (m::'a \text{ literal multiset}) M = M \cup \{m\} \vee m \notin M$ 
        using f3 f2 Un-empty-right add.right-neutral insert-iff by fastforce
      then have  $\Xi \ (N - \{A + \{\#L\# \} + \{\#L\# \}) < \Xi \ N$ 
        using f5 f4 by (metis Un-empty-right  $\langle \Xi \ \{A + \{\#L\# \}\rangle < \Xi \ \{A + \{\#L\# \} + \{\#L\# \}\rangle$ 
          add.right-neutral add-diff-cancel-left' add-gr-0 diff-less fin finite.emptyI not-le
          sum-count-ge-2.empty sum-count-ge-2.insert-remove trans-le-add2)
      then show ?thesis
        using f3 f2 a1 by (metis (no-types) Un-empty-right Un-insert-right condensation.hyps
          insert-iff multi-self-add-other-not-self)
    qed
  next
    assume  $?C' \notin N$ 
    have mset-decomp:
       $\{\# La \in \# A. (L = La \longrightarrow \text{Suc } 0 \leq \text{count } A \ La) \wedge (L \neq La \longrightarrow 2 \leq \text{count } A \ La)\#\}$ 
      =  $\{\# La \in \# A. L \neq La \wedge 2 \leq \text{count } A \ La\# \} +$ 
       $\{\# La \in \# A. L = La \wedge \text{Suc } 0 \leq \text{count } A \ L\#\}$ 
      by (auto simp: multiset-eq-iff ac-simps)
    have mset-decomp2:  $\{\# La \in \# A. L \neq La \longrightarrow 2 \leq \text{count } A \ La\# \} =$ 
       $\{\# La \in \# A. L \neq La \wedge 2 \leq \text{count } A \ La\# \} + \text{replicate-mset } (\text{count } A \ L) \ L$ 
      by (auto simp: multiset-eq-iff)

    show ?thesis
      using  $\langle \Xi \ \{A + \{\#L\# \}\rangle < \Xi \ \{A + \{\#L\# \} + \{\#L\# \}\rangle$  condensation.hyps fin
        sum-count-ge-2.remove[of - A +  $\{\#L\# \} + \{\#L\# \}$ ]  $\langle ?C' \notin N \rangle$ 
      by (auto simp: mset-decomp mset-decomp2 filter-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  $\text{card } (N - \{B\}) < \text{card } N$  using BN by (meson card-Diff1-less subsumption.prem)
moreover have  $\Xi \ (N - \{B\}) \leq \Xi \ N$ 
  by (simp add: Diff-subset finite-incl-le-setsum subsumption.prem)
ultimately show ?case by linarith
qed

lemma simplify-terminates:
  wf  $\{(N', N). \text{finite } N \wedge \text{simplify } N \ N'\}$ 
  apply (rule wfP-if-measure[of finite simplify  $\lambda N. \text{card } N + \Xi \ N$ ])

```

using *simplify-finite-measure-decrease* by *blast*

lemma *wf-terminates*:

assumes *wf r*

shows $\exists N'. (N', N) \in r^* \wedge (\forall N''. (N'', N') \notin r)$

proof –

let $?P = \lambda N. (\exists N'. (N', N) \in r^* \wedge (\forall N''. (N'', N') \notin r))$

have $(\forall x. (\forall y. (y, x) \in r \longrightarrow ?P y) \longrightarrow ?P x)$

proof *clarify*

fix *x*

assume *H*: $\forall y. (y, x) \in r \longrightarrow ?P y$

{ assume $\exists y. (y, x) \in r$

then obtain *y* where *y*: $(y, x) \in r$ by *blast*

then have $?P y$ using *H* by *blast*

then have $?P x$ using *y* by (*meson rtrancl.rtrancl-into-rtrancl*)

}

moreover {

assume $\neg(\exists y. (y, x) \in r)$

then have $?P x$ by *auto*

}

ultimately show $?P x$ by *blast*

qed

moreover have $(\forall x. (\forall y. (y, x) \in r \longrightarrow ?P y) \longrightarrow ?P x) \longrightarrow \text{All } ?P$

using *assms unfolding wf-def* by (*rule allE*)

ultimately have *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* $\{(N', N). \text{simplify } N N' \wedge \text{finite } N\}$

using *simplify-terminates* by (*simp add: H*)

obtain *N'* where *N'*: $(N', N) \in \{(b, a). \text{simplify } a b \wedge \text{finite } a\}^*$ and

more: $(\forall N''. (N'', N') \notin \{(b, a). \text{simplify } a b \wedge \text{finite } a\})$

using *Prop-Resolution.wf-terminates[OF wf, of N]* by *blast*

have *1*: $\text{simplify}^{**} N N'$

using *N'* by (*induction rule: rtrancl.induct*) *auto*

then have *finite N'* using *fin rtranclp-simplify-preserves-finite* by *blast*

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

show *?thesis* using *1 2* by *blast*

qed

lemma *finite-simplified-full1-simp*:

assumes *finite N*

shows $\text{simplified } N \vee (\exists N'. \text{full1 simplify } N N')$

using *rtranclp-simplify-terminates[OF assms]* *unfolding full1-def*

by (*metis Nitpick.rtranclp-unfold*)

lemma *finite-simplified-full-simp*:

assumes *finite N*

shows $\exists N'. \text{full simplify } N N'$

using *rtrancp-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* ψ) **and** *already-used-inv* ψ

and *partial-interps* *tree* *I* (*fst* ψ)

and *simplified* (*fst* ψ)

shows $\exists (\text{tree}' :: 'v \text{ sem-tree}) \psi'. \text{resolution}^{**} \psi \psi' \wedge \text{partial-interps } \text{tree}' I (\text{fst } \psi')$

$\wedge (\text{sem-tree-size } \text{tree}' < \text{sem-tree-size } \text{tree} \vee \text{sem-tree-size } \text{tree} = 0)$

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*: *xs* = *Node* *v* *ag* *ad* **using** *sn0* **by** (*cases* *xs*, *auto*)

{

assume *sem-tree-size* *ag* = 0 \wedge *sem-tree-size* *ad* = 0

then have *ag*: *ag* = *Leaf* **and** *ad*: *ad* = *Leaf* **by** (*cases* *ag*, *auto*, *cases* *ad*, *auto*)

{

then obtain χ χ' **where**

χ : $\neg I \cup \{\text{Pos } v\} \models \chi$ **and**

tot χ : *total-over-m* ($I \cup \{\text{Pos } v\}$) $\{\chi\}$ **and**

$\chi\psi$: $\chi \in \text{fst } \psi$ **and**

χ' : $\neg I \cup \{\text{Neg } v\} \models \chi'$ **and**

tot χ' : *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*: *Pos* *v* $\notin \# \chi$ **using** χ **unfolding** *true-cls-def* *true-lit-def* **by** *auto*

have *Negv*: *Neg* *v* $\notin \# \chi'$ **using** χ' **unfolding** *true-cls-def* *true-lit-def* **by** *auto*

{

assume *Neg* χ : *Neg* *v* $\notin \# \chi$

then have $\neg I \models \chi$ **using** χ *Posv* **unfolding** *true-cls-def* *true-lit-def* **by** *auto*

moreover have *total-over-m* *I* $\{\chi\}$

using *Posv* *Neg* χ *atm-imp-pos-or-neg-lit* *tot* χ **unfolding** *total-over-m-def* *total-over-set-def*
by *fastforce*

ultimately have *partial-interps* *Leaf* *I* (*fst* ψ)

and *sem-tree-size* *Leaf* < *sem-tree-size* *xs*

and *resolution*^{**} ψ ψ

unfolding *xs* **by** (*auto* *simp* *add*: $\chi\psi$)

}

moreover {

assume *Pos* χ : *Pos* *v* $\notin \# \chi'$

then have *I* χ : $\neg I \models \chi'$ **using** χ' *Posv* **unfolding** *true-cls-def* *true-lit-def* **by** *auto*

moreover have *total-over-m* *I* $\{\chi'\}$

using *Negv* *Pos* χ *atm-imp-pos-or-neg-lit* *tot* χ'

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

ultimately have *partial-interps* *Leaf* *I* (*fst* ψ)

and *sem-tree-size* *Leaf* < *sem-tree-size* *xs*

and *resolution*^{**} ψ ψ

using $\chi'\psi$ *I* χ **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 ( $simp\ add: dual-order.antisym$ )
  have  $count\ \chi'\ (Pos\ v) = 1$ 
    using  $simplified-count[OF\ simp\ \chi'\psi]$   $pos$ 
    by ( $simp\ add: dual-order.antisym$ )

  obtain  $C$  where  $\chi C: \chi = C + \{\#Neg\ v\# \}$  and  $negC: Neg\ v \notin \# C$  and  $posC: Pos\ v \notin \# C$ 
    by ( $metis\ (no-types,\ lifting)\ One-nat-def\ Posv\ Suc-eq-plus1-left\ \langle count\ \chi\ (Neg\ v) = 1 \rangle$ 
       $add-diff-cancel-left'\ count-diff\ count-greater-eq-one-iff\ count-single\ insert-DiffM$ 
       $insert-DiffM2\ less-numeral-extra(3)\ multi-member-skip\ not-le\ not-less-eq-eq$ )

  obtain  $C'$  where
     $\chi C': \chi' = C' + \{\#Pos\ v\# \}$  and
     $posC': Pos\ v \notin \# C'$  and
     $negC': Neg\ v \notin \# C'$ 
    by ( $metis\ (no-types,\ lifting)\ One-nat-def\ Negv\ Suc-eq-plus1-left\ \langle count\ \chi'\ (Pos\ v) = 1 \rangle$ 
       $add-diff-cancel-left'\ count-diff\ count-greater-eq-one-iff\ count-single\ insert-DiffM$ 
       $insert-DiffM2\ less-numeral-extra(3)\ multi-member-skip\ not-le\ not-less-eq-eq$ )

  have  $totC: total-over-m\ I\ \{C\}$ 
    using  $tot\chi\ tot-over-m-remove[of\ I\ Pos\ v\ C]\ negC\ posC$  unfolding  $\chi C$ 
    by ( $metis\ total-over-m-sum\ uminus-Neg\ uminus-of-uminus-id$ )
  have  $totC': total-over-m\ I\ \{C'\}$ 
    using  $tot\chi'\ total-over-m-sum\ tot-over-m-remove[of\ I\ Neg\ v\ C']\ negC'\ posC'$ 
    unfolding  $\chi C'$  by ( $metis\ total-over-m-sum\ uminus-Neg$ )
  have  $\neg I \models C + C'$ 
    using  $\chi\ \chi'\ \chi C\ \chi C'$  by  $auto$ 
  then have  $part-I-\psi''': partial-interps\ Leaf\ I\ (fst\ \psi \cup \{C + C'\})$ 
    using  $totC\ totC'\ \neg I \models C + C'$  by ( $metis\ Un-insert-right\ insertI1$ 
       $partial-interps.simps(1)\ total-over-m-sum$ )
  {
    assume  $(\{\#Pos\ v\# \} + C', \{\#Neg\ v\# \} + C) \notin snd\ \psi$ 
    then have  $inf''': inference\ \psi\ (fst\ \psi \cup \{C + C'\}, snd\ \psi \cup \{(\chi', \chi)\})$ 
      by ( $metis\ \chi'\psi\ \chi C\ \chi C'\ \chi\psi\ add.commute\ inference-step\ prod.collapse\ resolution$ )
    obtain  $N'$  where  $full: full\ simplify\ (fst\ \psi \cup \{C + C'\})\ N'$ 
      by ( $metis\ finite-simplified-full-simp\ fst-conv\ inf'''\ inference-preserves-finite$ 
         $local.finite$ )
    have  $resolution\ \psi\ (N', snd\ \psi \cup \{(\chi', \chi)\})$ 
      using  $resolution.intros(2)[OF\ -\ simp\ full,\ of\ snd\ \psi\ snd\ \psi \cup \{(\chi', \chi)\}]\ inf'''$ 
      by ( $metis\ surjective-pairing$ )
    moreover have  $partial-interps\ Leaf\ I\ N'$ 
      using  $full-simplify-preserve-partial-tree[OF\ full\ part-I-\psi''']$  .
    moreover have  $sem-tree-size\ Leaf < sem-tree-size\ xs$  unfolding  $xs$  by  $auto$ 
    ultimately have  $?case$ 
      by ( $metis\ (no-types)\ prod.sel(1)\ rtranclp.rtrancl-into-rtrancl\ rtranclp.rtrancl-refl$ )
  }
}

moreover {
  assume  $a: (\{\#Pos\ v\# \} + C', \{\#Neg\ v\# \} + C) \in snd\ \psi$ 
  then have  $(\exists \chi \in fst\ \psi. (\forall I. total-over-m\ I\ \{C+C'\} \longrightarrow total-over-m\ I\ \{\chi\})$ 
     $\wedge (\forall I. total-over-m\ I\ \{\chi\} \longrightarrow I \models \chi \longrightarrow I \models C' + C)) \vee tautology\ (C' + C)$ 
  proof -
    obtain  $p$  where  $p: Pos\ p \in \# (\{\#Pos\ v\# \} + C') \wedge Neg\ p \in \# (\{\#Neg\ v\# \} + C)$ 
       $\wedge ((\exists \chi \in fst\ \psi. (\forall I. total-over-m\ I\ \{(\{\#Pos\ v\# \} + C') - \{\#Pos\ p\# \} + (\{\#Neg\ v\# \}$ 

```

```

+ C) - {#Neg p#})} → total-over-m I {χ} ∧ (∀ I. total-over-m I {χ} → I ⊨ χ → I ⊨ ({#Pos
v#} + C') - {#Pos p#} + (({#Neg v#} + C) - {#Neg p#}))) ∨ tautology (({#Pos v#} + C') -
{#Pos p#} + (({#Neg v#} + C) - {#Neg p#})))
  using a by (blast intro: allE[OF a-u-i[unfolded subsumes-def Ball-def],
    of ({#Pos v#} + C', {#Neg v#} + C)])
  { assume p ≠ v
    then have Pos p ∈# C' ∧ Neg p ∈# C using p by force
    then have ?thesis by auto
  }
  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 ∃χ ∈ fst ψ. (∀ I. total-over-m I {C+C'} → total-over-m I {χ})
  ∧ (∀ I. total-over-m I {χ} → I ⊨ χ → I ⊨ C' + C)
  then obtain ϑ where
    ϑ: ϑ ∈ fst ψ and
    tot-ϑ-CC': ∀ I. total-over-m I {C+C'} → total-over-m I {ϑ} and
    ϑ-inv: ∀ I. total-over-m I {ϑ} → I ⊨ ϑ → I ⊨ C' + C by blast
  have partial-interps Leaf I (fst ψ)
    using tot-ϑ-CC' ϑ ϑ-inv totC totC' ⊢ I ⊨ 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 ¬tautology (C' + C)
    using ⊢ I ⊨ C + C' unfolding add.commute[of C C'] total-over-m-def
    unfolding tautology-def by auto
  then have False using tautCC' unfolding tautology-def by auto
}
ultimately have ?case by auto
}
ultimately have ?case by auto
}
ultimately have ?case using part by (metis (no-types) sem-tree-size.simps(1))
}
moreover {
  assume size-ag: sem-tree-size ag > 0
  have sem-tree-size ag < sem-tree-size xs unfolding xs by auto
  moreover have partial-interps ag (I ∪ {Pos v}) (fst ψ)
  and partad: partial-interps ad (I ∪ {Neg v}) (fst ψ)
  using part partial-interps.simps(2) unfolding xs by metis+
  moreover
    have sem-tree-size ag < sem-tree-size xs ⇒ finite (fst ψ) ⇒ already-used-inv ψ
    ⇒ partial-interps ag (I ∪ {Pos v}) (fst ψ) ⇒ simplified (fst ψ)
    ⇒ ∃ tree' ψ'. resolution** ψ ψ' ∧ partial-interps tree' (I ∪ {Pos v}) (fst ψ')
    ∧ (sem-tree-size tree' < sem-tree-size ag ∨ sem-tree-size ag = 0)
    using IH[of ag I ∪ {Pos v}] by auto
  ultimately obtain ψ' :: 'v state and tree' :: 'v sem-tree where
    inf: resolution** ψ ψ'
    and part: partial-interps tree' (I ∪ {Pos v}) (fst ψ')

```

```

    and size: sem-tree-size tree' < sem-tree-size ag ∨ sem-tree-size ag = 0
    using finite part rtranclp.rtrancl-refl a-u-i simp by blast

  have partial-interps ad (I ∪ {Neg v}) (fst ψ')
    using rtranclp-resolution-preserve-partial-tree inf partad by fast
  then have partial-interps (Node v tree' ad) I (fst ψ') using part by auto
  then have ?case using inf size size-ag part unfolding xs by fastforce
}
moreover {
  assume size-ad: sem-tree-size ad > 0
  have sem-tree-size ad < sem-tree-size xs unfolding xs by auto
  moreover
    have
      partag: partial-interps ag (I ∪ {Pos v}) (fst ψ) and
      partial-interps ad (I ∪ {Neg v}) (fst ψ)
      using part partial-interps.simps(2) unfolding xs by metis+
  moreover have sem-tree-size ad < sem-tree-size xs ⟶ finite (fst ψ) ⟶ already-used-inv ψ
    ⟶ ( partial-interps ad (I ∪ {Neg v}) (fst ψ) ⟶ simplified (fst ψ)
    ⟶ (∃ tree' ψ'. resolution** ψ ψ' ∧ partial-interps tree' (I ∪ {Neg v}) (fst ψ')
    ∧ (sem-tree-size tree' < sem-tree-size ad ∨ sem-tree-size ad = 0)))
    using IH by blast
  ultimately obtain ψ' :: 'v state and tree' :: 'v sem-tree where
    inf: resolution** ψ ψ'
    and part: partial-interps tree' (I ∪ {Neg v}) (fst ψ')
    and size: sem-tree-size tree' < sem-tree-size ad ∨ sem-tree-size ad = 0
    using finite part rtranclp.rtrancl-refl a-u-i simp by blast

  have partial-interps ag (I ∪ {Pos v}) (fst ψ')
    using rtranclp-resolution-preserve-partial-tree inf partag by fast
  then have partial-interps (Node v ag tree') I (fst ψ') using part by auto
  then have ?case using inf size size-ad unfolding xs by fastforce
}
ultimately have ?case by auto
}
ultimately show ?case by auto
qed

lemma resolution-completeness-inv:
  fixes ψ :: 'v :: linorder state
  assumes
    unsat: ¬satisfiable (fst ψ) and
    finite: finite (fst ψ) and
    a-u-v: already-used-inv ψ
  shows ∃ ψ'. (resolution** ψ ψ' ∧ {#} ∈ fst ψ')
proof -
  obtain tree where partial-interps tree {} (fst ψ)
  using partial-interps-build-sem-tree-atms assms by metis
  then show ?thesis
  using unsat finite a-u-v
  proof (induct tree arbitrary: ψ rule: sem-tree-size)
    case (bigger tree ψ) note H = this
    {
      fix χ
      assume tree: tree = Leaf
      obtain χ where χ: ¬ {} ⊨ χ and totχ: total-over-m {} {χ} and χψ: χ ∈ fst ψ
      using H unfolding tree by auto
    }
  qed

```

```

moreover have {#} =  $\chi$ 
  using H atms-empty-iff-empty tot $\chi$ 
  unfolding true-cls-def total-over-m-def total-over-set-def by fastforce
moreover have resolution**  $\psi$   $\psi$  by auto
ultimately have ?case by metis
}
moreover {
  fix v tree1 tree2
  assume tree: tree = Node v tree1 tree2
  obtain  $\psi_0$  where  $\psi_0$ : resolution**  $\psi$   $\psi_0$  and simp: simplified (fst  $\psi_0$ )
  proof –
    { assume simplified (fst  $\psi$ )
      moreover have resolution**  $\psi$   $\psi$  by auto
      ultimately have thesis using that by blast
    }
  moreover {
    assume  $\neg$ simplified (fst  $\psi$ )
    then have  $\exists \psi'. \text{full1 simplify (fst } \psi) \psi'$ 
      by (metis Nitpick.rtranclp-unfold bigger.prem(3) full1-def
        rtranclp-simplify-terminates)
    then obtain N where full1 simplify (fst  $\psi$ ) N by metis
    then have resolution  $\psi$  (N, snd  $\psi$ )
      using resolution.intros(1)[of fst  $\psi$  N snd  $\psi$ ] by auto
    moreover have simplified N
      using  $\langle \text{full1 simplify (fst } \psi) N \rangle$  unfolding full1-def by blast
    ultimately have ?thesis using that by force
  }
  ultimately show ?thesis by auto
}
qed

have p: partial-interps tree {} (fst  $\psi_0$ )
and uns: unsatisfiable (fst  $\psi_0$ )
and f: finite (fst  $\psi_0$ )
and a-u-v: already-used-inv  $\psi_0$ 
  using  $\psi_0$  bigger.prem(1) rtranclp-resolution-preserve-partial-tree apply blast
  using  $\psi_0$  bigger.prem(2) rtranclp-resolution-preserves-unsat apply blast
  using  $\psi_0$  bigger.prem(3) rtranclp-resolution-finite apply blast
  using rtranclp-resolution-already-used-inv[OF  $\psi_0$  bigger.prem(4)] by blast
obtain tree'  $\psi'$  where
  inf: resolution**  $\psi_0$   $\psi'$  and
  part': partial-interps tree' {} (fst  $\psi'$ ) and
  decrease: sem-tree-size tree' < sem-tree-size tree  $\vee$  sem-tree-size tree = 0
  using can-decrease-tree-size-resolution[OF f a-u-v p simp] unfolding tautology-def
  by meson
have s: sem-tree-size tree' < sem-tree-size tree using decrease unfolding tree by auto
have fin: finite (fst  $\psi'$ )
  using f inf rtranclp-resolution-finite by blast
have unsat: unsatisfiable (fst  $\psi'$ )
  using rtranclp-resolution-preserves-unsat inf uns by metis
have a-u-i': already-used-inv  $\psi'$ 
  using a-u-v inf rtranclp-resolution-already-used-inv[of  $\psi_0$   $\psi'$ ] by auto
have ?case
  using inf rtranclp-trans[of resolution] H(1)[OF s part' unsat fin a-u-i']  $\psi_0$  by blast
}
ultimately show ?case by (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 *rtranclp-resolution-preserves-already-used-inv*:
 assumes *resolution*** $S\ S'$
 and *already-used-inv* S
 shows *already-used-inv* S'
 using *assms*
 apply (induct rule: *rtranclp-induct*)
 apply *simp*
 using *resolution-preserves-already-used-inv* by *fast*

lemma *resolution-completeness*:
 fixes $\psi :: 'v :: \text{linorder state}$
 assumes *unsat*: $\neg \text{satisfiable (fst } \psi)$
 and *finite*: *finite* (fst ψ)
 and *snd* $\psi = \{\}$
 shows $\exists \psi'. (\text{resolution** } \psi\ \psi' \wedge \{\#\} \in \text{fst } \psi')$
proof –
 have *already-used-inv* ψ **unfolding** *assms* **by** *auto*
 then show ?thesis **using** *assms resolution-completeness-inv* **by** *blast*
 qed

lemma *rtranclp-preserves-sat*:
 assumes *simplify*** $S\ S'$
 and *satisfiable* S
 shows *satisfiable* S'
 using *assms* **apply** *induction*
apply *simp*
by (*meson satisfiable-carac satisfiable-def simplify-preserves-un-sat-eq*)

lemma *resolution-preserves-sat*:
 assumes *resolution* $S\ S'$
 and *satisfiable* (fst S)
 shows *satisfiable* (fst S')
 using *assms* **apply** (*induction* rule: *resolution.induct*)
 using *rtranclp-preserves-sat* *tranclp-into-rtranclp* **unfolding** *full1-def* **apply** *fastforce*
by (*metis fst-conv full-def inference-preserves-un-sat rtranclp-preserves-sat*
satisfiable-carac' satisfiable-def)

lemma *rtranclp-resolution-preserves-sat*:
 assumes *resolution*** $S\ S'$
 and *satisfiable* (fst S)
 shows *satisfiable* (fst S')

```

using assms apply (induction rule: rtrancpl-induct)
apply simp
using resolution-preserves-sat by blast

lemma resolution-soundness:
  fixes  $\psi :: 'v :: \text{linorder state}$ 
  assumes resolution**  $\psi \ \psi'$  and  $\{\#\} \in \text{fst } \psi'$ 
  shows unsatisfiable (fst  $\psi$ )
  using assms by (meson rtrancpl-resolution-preserves-sat satisfiable-def true-cls-empty
    true-cls-def)

lemma resolution-soundness-and-completeness:
  fixes  $\psi :: 'v :: \text{linorder state}$ 
  assumes finite: finite (fst  $\psi$ )
  and snd: snd  $\psi = \{\}$ 
  shows  $(\exists \psi'. (\text{resolution** } \psi \ \psi' \wedge \{\#\} \in \text{fst } \psi')) \longleftrightarrow \text{unsatisfiable } (\text{fst } \psi)$ 
  using assms resolution-completeness resolution-soundness by metis

lemma simplified-falsity:
  assumes simp: simplified  $\psi$ 
  and  $\{\#\} \in \psi$ 
  shows  $\psi = \{\{\#\}\}$ 
proof (rule ccontr)
  assume H:  $\neg ?thesis$ 
  then obtain  $\chi$  where  $\chi \in \psi$  and  $\chi \neq \{\#\}$  using assms(2) by blast
  then have  $\{\#\} \subsetneq \chi$  by (simp add: mset-less-empty-nonempty)
  then have simplify  $\psi$  ( $\psi - \{\chi\}$ )
    using simplify.subsumption[OF assms(2)  $\langle \{\#\} \subsetneq \chi \rangle \langle \chi \in \psi \rangle$ ] by blast
  then show False using simp by blast
qed

lemma simplify-falsity-in-preserved:
  assumes simplify  $\chi s \ \chi s'$ 
  and  $\{\#\} \in \chi s$ 
  shows  $\{\#\} \in \chi s'$ 
  using assms
  by induction auto

lemma rtrancpl-simplify-falsity-in-preserved:
  assumes simplify**  $\chi s \ \chi s'$ 
  and  $\{\#\} \in \chi s$ 
  shows  $\{\#\} \in \chi s'$ 
  using assms
  by induction (auto intro: simplify-falsity-in-preserved)

lemma resolution-falsity-get-falsity-alone:
  assumes finite (fst  $\psi$ )
  shows  $(\exists \psi'. (\text{resolution** } \psi \ \psi' \wedge \{\#\} \in \text{fst } \psi')) \longleftrightarrow (\exists a-u-v. \text{resolution** } \psi (\{\{\#\}\}, a-u-v))$ 
  (is  $?A \longleftrightarrow ?B$ )
proof
  assume  $?B$ 
  then show  $?A$  by auto
next
  assume  $?A$ 
  then obtain  $\chi s \ a-u-v$  where  $\chi s$ : resolution**  $\psi (\chi s, a-u-v)$  and  $F$ :  $\{\#\} \in \chi s$  by auto

```

```

{ assume simplified  $\chi s$ 
  then have ?B using simplified-falsity[OF - F]  $\chi s$  by blast
}
moreover {
  assume  $\neg$  simplified  $\chi s$ 
  then obtain  $\chi s'$  where full1 simplify  $\chi s \chi s'$ 
    by (metis  $\chi s$  assms finite-simplified-full1-simp fst-conv rtranclp-resolution-finite)
  then have  $\{\#\} \in \chi s'$ 
    unfolding full1-def by (meson F rtranclp-simplify-falsity-in-preserved
      trancpl-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 Prop-Superposition
imports Partial-Clausal-Logic ../lib/Herbrand-Interpretation
begin

```

4.2 Superposition

```

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*:

$S \models_{hs} C \iff \{Pos\ P | P. P \in S\} \cup \{Neg\ P | P. P \notin S\} \models_s C$

unfolding *true-clss-def Ball-def herbrand-interp-iff-partial-interp-clss*

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 ($-\hat{<}^{bsup}>-\hat{<}^{esup}>$)

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 = $\{A. C \in N \wedge C \neq \{\#\} \wedge \text{Max}(\text{set-mset } C) = \text{Pos } A \wedge \text{count } C (\text{Pos } A) \leq 1 \wedge \neg$
 $\neg \text{interp } C \models_h C \wedge S\ C = \{\#\}\}$

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 $\implies C \in N \wedge C \neq \{\#\} \wedge \text{Pos } A = \text{Max}(\text{set-mset } C) \wedge \text{count } C (\text{Pos } A) \leq 1 \wedge$
 $\neg \text{interp } C \models_h C \wedge S\ C = \{\#\}$

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 = ($\bigcup D \in \{D \in N. D \# \subseteq \# C\}. \text{production } D$)
unfolding *interp-def* **apply** *auto*
unfolding *production-unfold* **apply** *auto*
done

lemma *production-iff-produces:*
produces D A \longleftrightarrow A \in production D
unfolding *production-unfold* **by** *auto*

definition *Interp :: 'a clause \Rightarrow 'a interp where*
Interp C = interp C \cup production C

lemma
assumes *produces C P*
shows *Interp C \models_h C*
unfolding *Interp-def* **assms** **using** *producesD[OF assms]*
by (*metis Max-in-lits Un-insert-right insertI1 pos-literal-in-imp-true-cls*)

definition *INTERP :: 'a interp where*
INTERP = ($\bigcup D \in N. \text{production } D$)

lemma *interp-subseteq-Interp[simp]: interp C \subseteq Interp C*
unfolding *Interp-def* **by** *simp*

lemma *Interp-as-UNION: 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: productive C \implies C $\neq \{\#\}$*
unfolding *production-unfold* **by** *auto*

lemma *productive-imp-produces-Max-literal: productive C \implies produces C (atm-of (Max (set-mset C)))*
unfolding *production-unfold* **by** (*auto simp del: atm-of-Max-lit*)

lemma *productive-imp-produces-Max-atom: productive C \implies produces C (Max (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: produces C A \implies A = atm-of (Max (set-mset C))*
by (*metis Max-singleton insert-not-empty productive-imp-produces-Max-literal*)

lemma *produces-imp-Max-atom: produces C A \implies A = Max (atms-of C)*
by (*metis Max-singleton insert-not-empty productive-imp-produces-Max-atom*)

lemma *produces-imp-Pos-in-lits: produces C A \implies Pos A $\in \#$ C*
by (*auto intro: Max-in-lits dest!: producesD*)

lemma *productive-in-N: productive C \implies C \in N*
unfolding *production-unfold* **by** *auto*

lemma *produces-imp-atms-leq: produces C A \implies B \in 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*: $\text{produces } C \ A \implies \text{Neg } A \notin \# \ C$
by (*rule pos-Max-imp-neg-notin*) (*auto dest: producesD*)

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*: $C \# \subseteq \# \ D \implies \text{production } C \subseteq \text{interp } D$
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*: $C \# \subseteq \# \ D \implies \text{Interp } C \subseteq \text{interp } D$
unfolding *Interp-def*
by (*auto simp: less-eq-imp-interp-subseteq-interp less-imp-production-subseteq-interp*)

lemma *less-eq-imp-Interp-subseteq-Interp*: $C \# \subseteq \# \ D \implies \text{Interp } C \subseteq \text{Interp } D$
using *less-imp-Interp-subseteq-interp*
unfolding *Interp-def* **by** (*metis multiset-order.le-imp-less-or-eq le-supI2 subset-refl sup-commute*)

lemma *false-Interp-to-true-interp-imp-less-multiset*: $A \notin \text{Interp } C \implies A \in \text{interp } D \implies C \# \subseteq \# \ D$
using *less-eq-imp-interp-subseteq-Interp multiset-linorder.not-less* **by** *blast*

lemma *false-interp-to-true-interp-imp-less-multiset*: $A \notin \text{interp } C \implies A \in \text{interp } D \implies C \# \subseteq \# \ D$
using *less-eq-imp-interp-subseteq-interp multiset-linorder.not-less* **by** *blast*

lemma *false-Interp-to-true-Interp-imp-less-multiset*: $A \notin \text{Interp } C \implies A \in \text{Interp } D \implies C \# \subseteq \# \ D$
using *less-eq-imp-Interp-subseteq-Interp multiset-linorder.not-less* **by** *blast*

lemma *false-interp-to-true-Interp-imp-le-multiset*: $A \notin \text{interp } C \implies A \in \text{Interp } D \implies C \# \subseteq \# \ D$
using *less-imp-Interp-subseteq-interp multiset-linorder.not-less* **by** *blast*

lemma *interp-subseteq-INTERP*: $\text{interp } C \subseteq \text{INTERP}$
unfolding *interp-def INTERP-def* **by** (*auto simp: production-unfold*)

lemma *production-subseteq-INTERP*: $\text{production } C \subseteq \text{INTERP}$
unfolding *INTERP-def* **using** *production-unfold* **by** *blast*

lemma *Interp-subseteq-INTERP*: $\text{Interp } C \subseteq \text{INTERP}$
unfolding *Interp-def* **by** (*auto intro!: interp-subseteq-INTERP production-subseteq-INTERP*)

This lemma corresponds to theorem 2.7.6 page 67 of Weidenbach's book.

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*
then have $D \# \subseteq \# \ \{\# \ \text{Neg } A \# \}$
by (*auto intro: Max-pos-neg-less-multiset*)

moreover have $\{\#Neg\ A\#\} \# \subseteq \# C$
by (rule less-eq-imp-le-multiset) (rule mset-le-single[OF a-in-c])
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: $Neg\ A \in \# C \implies A \notin Interp\ D \implies C \# \subseteq \# D \implies \neg\ produces\ D''\ A$
by (auto dest: produces-imp-in-interp less-eq-imp-interp-subseteq-Interp)

lemma in-production-imp-produces: $A \in production\ C \implies produces\ C\ A$
by (metis insert-absorb productive-imp-produces-Max-atom singleton-insert-inj-eq')

lemma not-produces-imp-notin-production: $\neg\ produces\ C\ A \implies A \notin production\ C$
by (metis in-production-imp-produces)

lemma not-produces-imp-notin-interp: $(\bigwedge D. \neg\ produces\ D\ A) \implies A \notin interp\ C$
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: $Interp\ D \models_h C$ **and**
subs: $interp\ D' \subseteq (\bigcup C \in CC. production\ C)$
shows $(\bigcup C \in CC. production\ C) \models_h C$
proof (cases $\exists A. Pos\ A \in \# C \wedge A \in Interp\ D$)
case True
then obtain A **where** a-in-c: $Pos\ A \in \# C$ **and** a-at-d: $A \in Interp\ D$
by blast
from a-at-d **have** $A \in interp\ D'$
using d-lt-d' less-imp-Interp-subseteq-interp **by** blast
then show ?thesis
using subs a-in-c **by** (blast dest: contra-subsetD)
next
case False
then obtain A **where** a-in-c: $Neg\ A \in \# C$ **and** $A \notin Interp\ D$
using c-at-d **unfolding** true-cls-def **by** blast
then have $\bigwedge D''. \neg\ produces\ D''\ A$
using c-le-d neg-notin-Interp-not-produce **by** simp
then show ?thesis
using a-in-c subs not-produces-imp-notin-production **by** auto
qed

lemma true-Interp-imp-interp: $C \# \subseteq \# D \implies D \# \subset \# D' \implies Interp\ D \models_h C \implies interp\ D' \models_h C$
using interp-def true-Interp-imp-general **by** simp

lemma true-Interp-imp-Interp: $C \# \subseteq \# D \implies D \# \subset \# D' \implies Interp\ D \models_h C \implies Interp\ D' \models_h C$
using Interp-as-UNION interp-subseteq-Interp true-Interp-imp-general **by** simp

lemma true-Interp-imp-INTERP: $C \# \subseteq \# D \implies Interp\ D \models_h C \implies INTERP \models_h C$
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*

then show *?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*

then have $\bigwedge D''. \neg \text{produces } D'' A$

using *c-le-d* **by** (*auto dest: produces-imp-in-interp less-eq-imp-interp-subseteq-interp*)

then show *?thesis*

using *a-in-c subs not-produces-imp-notin-production* **by** *auto*

qed

This lemma corresponds to theorem 2.7.6 page 67 of Weidenbach's book. 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 67 of Weidenbach's book. Here the strict maximality is important

lemma *cls-gt-double-pos-no-production*:

assumes *D*: $\{\# \text{Pos } P, \text{Pos } P \# \} \# \subset \# C$

shows $\neg \text{produces } C P$

proof –

let $?D = \{\# \text{Pos } P, \text{Pos } P \# \}$

note $D' = D[\text{unfolded less-multiset}_{HO}]$

consider

(*P*) *count* *C* (*Pos* *P*) ≥ 2

| (*Q*) *Q* **where** $Q > \text{Pos } P$ **and** $Q \in \# C$

using *HOL.spec*[*OF HOL.conjunct2*[*OF D'*], *of Pos P*] **by** (*auto split: if-split-asm*)

```

then show ?thesis
proof cases
  case Q
  have  $Q \in \text{set-mset } C$ 
    using  $Q(2)$  by (auto split: if-split-asm)
  then have  $\text{Max } (\text{set-mset } C) > \text{Pos } P$ 
    using  $Q(1)$  Max-gr-iff by blast
  then show ?thesis
    unfolding production-unfold by auto
next
  case P
  then show ?thesis
    unfolding production-unfold by auto
qed
qed

```

This lemma corresponds to theorem 2.7.6 page 67 of Weidenbach's book.

lemma

assumes $D: C + \{\# \text{Neg } P \# \} \# \subset \# D$
 shows $\text{production } D \neq \{P\}$

proof –

note $D' = D[\text{unfolded less-multiset}_{HO}]$

consider

(P) $\text{Neg } P \in \# D$

| (Q) Q where $Q > \text{Neg } P$ and $\text{count } D \ Q > \text{count } (C + \{\# \text{Neg } P \# \}) \ Q$

using $\text{HOL.spec}[OF \ \text{HOL.conjunct2}[OF \ D], \text{ of } \text{Neg } P] \text{ count-greater-zero-iff}$ by fastforce

then show ?thesis

proof cases

case Q

have $Q \in \text{set-mset } D$

using $Q(2)$ *gr-implies-not0* by fastforce

then have $\text{Max } (\text{set-mset } D) > \text{Neg } P$

using $Q(1)$ *Max-gr-iff* by blast

then have $\text{Max } (\text{set-mset } D) > \text{Pos } P$

using $\text{less-trans}[of \ \text{Pos } P \ \text{Neg } P \ \text{Max } (\text{set-mset } D)]$ by auto

then show ?thesis

unfolding production-unfold by auto

next

case P

then have $\text{Max } (\text{set-mset } D) > \text{Pos } P$

by (meson *Max-ge finite-set-mset le-less-trans linorder-not-le pos-less-neg*)

then show ?thesis

unfolding production-unfold by auto

qed

qed

lemma *in-interp-is-produced:*

assumes $P \in \text{INTERP}$

shows $\exists D. D + \{\# \text{Pos } P \# \} \in N \wedge \text{produces } (D + \{\# \text{Pos } P \# \}) \ P$

using *assms* unfolding *INTERP-def UN-iff production-iff-produces Ball-def*

by (metis *ground-resolution-with-selection.produces-imp-Pos-in-lits insert-DiffM2*
ground-resolution-with-selection-axioms not-produces-imp-notin-production)

end

end

abbreviation $MMax\ M \equiv Max\ (set-mset\ M)$

4.2.1 We can now define the rules of the calculus

inductive *superposition-rules* :: 'a clause \Rightarrow 'a clause \Rightarrow 'a clause \Rightarrow bool **where**
factoring: *superposition-rules* ($C + \{\#Pos\ P\# \} + \{\#Pos\ P\# \}$) $B\ (C + \{\#Pos\ P\# \}) \mid$
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 $C\ N = (cls-lt\ N\ C \models_p C)$

lemma *less-multiset[iff]*: $M < N \longleftrightarrow M \# \subset \# N$
unfolding *less-multiset-def* **by** *auto*

lemma *less-eq-multiset[iff]*: $M \leq N \longleftrightarrow M \# \subseteq \# N$
unfolding *less-eq-multiset-def* **by** *auto*

lemma *herbrand-true-clss-true-clss-cls-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 $IH: \bigwedge I. total-over-set\ I\ (atms-of\ C) \Longrightarrow total-over-m\ I\ B \Longrightarrow consistent-interp\ I$
 $\Longrightarrow I \models_s B \Longrightarrow I \models C$ **using** BC

by (*auto simp add: true-clss-cls-def*)

show *?thesis*

unfolding *herbrand-interp-iff-partial-interp-cls*

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*

then show *?thesis*

using *abstr unfolding abstract-red-def clss-lt-def*

by (*metis (no-types, lifting) c-lt-d subset-mset.diff-add true-clss-cls-mono-r' true-clss-cls-subset*)

qed

lemma *true-clss-clb-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 $?I = I \cup \{Pos\ P \mid P. P \in \text{atms-of } B \wedge P \notin \text{atms-of-s } I\}$

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 $aa :: 'a \text{ set} \Rightarrow 'a \text{ literal set} \Rightarrow 'a$ **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 $\forall a. a \notin \text{atms-of-ms } A \vee Pos\ a \in I \vee Neg\ a \in I$

using *tot* **by** (*simp* *add: total-over-m-def* *total-over-set-def*)

then **have** $aa\ (\text{atms-of-ms } A \cup \text{atms-of-ms } \{B\})\ (I \cup \{Pos\ a \mid a. a \in \text{atms-of } B \wedge a \notin \text{atms-of-s } I\})$

$\notin \text{atms-of-ms } A \cup \text{atms-of-ms } \{B\} \vee Pos\ (aa\ (\text{atms-of-ms } A \cup \text{atms-of-ms } \{B\}))$

$(I \cup \{Pos\ a \mid a. a \in \text{atms-of } B \wedge a \notin \text{atms-of-s } I\}) \in I$

$\cup \{Pos\ a \mid a. a \in \text{atms-of } B \wedge a \notin \text{atms-of-s } I\}$

$\vee Neg\ (aa\ (\text{atms-of-ms } A \cup \text{atms-of-ms } \{B\}))$

$(I \cup \{Pos\ a \mid a. a \in \text{atms-of } B \wedge a \notin \text{atms-of-s } I\}) \in I$

$\cup \{Pos\ a \mid a. a \in \text{atms-of } B \wedge a \notin \text{atms-of-s } I\}$

by *auto*

then **have** *total-over-set* $(I \cup \{Pos\ a \mid a. a \in \text{atms-of } B \wedge a \notin \text{atms-of-s } I\})$

$(\text{atms-of-ms } A \cup \text{atms-of-ms } \{B\})$

using $f2$ **by** (*meson* *total-over-set-def*)

then **show** *?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-clb-def* **by** *auto*

then **show** *?thesis*

oops

lemma

assumes

$CP: \neg \text{clss-lt } N\ (\{\#C\# \} + \{\#E\# \}) \models_p \{\#C\# \} + \{\#Neg\ P\# \}$ **and**

$\text{clss-lt } N\ (\{\#C\# \} + \{\#E\# \}) \models_p \{\#E\# \} + \{\#Pos\ P\# \} \vee \text{clss-lt } N\ (\{\#C\# \} + \{\#E\# \}) \models_p \{\#C\# \} + \{\#Neg\ P\# \}$

shows $\text{clss-lt } N\ (\{\#C\# \} + \{\#E\# \}) \models_p \{\#E\# \} + \{\#Pos\ P\# \}$

oops

locale *ground-ordered-resolution-with-redundancy* =

ground-resolution-with-selection +

fixes *redundant* :: $'a::\text{wellorder clause} \Rightarrow 'a \text{ clauses} \Rightarrow \text{bool}$

assumes

redundant-iff-abstract: $\text{redundant } A\ N \longleftrightarrow \text{abstract-red } A\ N$

begin

definition *saturated* :: 'a clauses \Rightarrow bool **where**

saturated $N \longleftrightarrow (\forall A B C. A \in N \longrightarrow B \in N \longrightarrow \neg \text{redundant } A N \longrightarrow \neg \text{redundant } B N$
 $\longrightarrow \text{superposition-rules } A B C \longrightarrow \text{redundant } C N \vee C \in N)$

lemma

assumes

saturated: *saturated* N **and**

finite: *finite* N **and**

empty: $\{\#\} \notin N$

shows *INTERP* $N \models_{hs} N$

proof (rule *ccontr*)

let $?N_{\mathcal{I}} = \text{INTERP } N$

assume $\neg ?thesis$

then have *not-empty*: $\{E \in N. \neg ?N_{\mathcal{I}} \models_h E\} \neq \{\}$

unfolding *true-clss-def Ball-def* **by** *auto*

def $D \equiv \text{Min } \{E \in N. \neg ?N_{\mathcal{I}} \models_h E\}$

have [*simp*]: $D \in N$

unfolding *D-def*

by (*metis* (*mono-tags*, *lifting*) *Min-in not-empty finite mem-Collect-eq rev-finite-subset subsetI*)

have *not-d-interp*: $\neg ?N_{\mathcal{I}} \models_h D$

unfolding *D-def*

by (*metis* (*mono-tags*, *lifting*) *Min-in finite mem-Collect-eq not-empty rev-finite-subset subsetI*)

have *cls-not-D*: $\bigwedge E. E \in N \implies E \neq D \implies \neg ?N_{\mathcal{I}} \models_h E \implies D \leq E$

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

then have $L \in \# D$

using *S-selects-subseteq*[of D] **by** *auto*

then have $D = (D - \{\#L\#$

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* ($D \in N$) *empty*)

then have $D = (D - \{\#?L\#$

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*

then have $?N_{\mathcal{I}} \models_{hs} \text{clss-lt } N D$

unfolding *clss-lt-def true-clss-def Ball-def* **by** *blast*

then show *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 = Pos P and S D = {#} and Max (set-mset D) = Pos P
| (Lneg) P where L = Neg P
  using LSD S-selects-neg-lits[of L D] by (cases L) auto
then show False
proof cases
  case L note P = this(1) and S = this(2) and max = this(3)
  have count D L > 1
  proof (rule ccontr)
    assume ~ ?thesis
    then have count: count D L = 1
    unfolding D by (auto simp: not-in-iff)
    have  $\neg N_{\mathcal{I}} \models_h D$ 
    using not-d-interp true-interp-imp-INTERP ground-resolution-with-selection-axioms
    by blast
    then have produces N D P
    using not-empty empty finite  $\langle D \in N \rangle$  count L
    true-interp-imp-INTERP unfolding production-iff-produces unfolding production-unfold
    by (auto simp add: max not-empty)
    then have INTERP N  $\models_h D$ 
    unfolding D
    by (metis pos-literal-in-imp-true-clss produces-imp-Pos-in-lits
    production-subseteq-INTERP singletonI subsetCE)
    then show False
    using not-d-interp by blast
  qed
  then have Pos P  $\in \# C$ 
  by (simp add: P D)
  then obtain C' where C':D = C' + {#Pos P#} + {#Pos P#}
  unfolding D by (metis (full-types) P insert-DiffM2)
  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' clss-not-D less-multiset
  multi-self-add-other-not-self not-le)
  have D - {#L#}  $\# \subset \# D$ 
  unfolding C' L by auto
  have c'-p-p: C' + {#Pos P#} + {#Pos P#} - {#Pos P#} = C' + {#Pos P#}
  by auto
  have redundant (C' + {#Pos P#}) N
  using saturated red sup  $\langle D \in N \rangle \langle C' + \{ \#Pos P \# \} \notin N \rangle$  unfolding saturated-def C' L c'-p-p
  by blast
  moreover have C' + {#Pos P#}  $\subseteq \# C' + \{ \#Pos P \# \} + \{ \#Pos P \# \}$ 
  by auto
  ultimately show False
  using red unfolding C' redundant-iff-abstract by (blast dest:
  abstract-red-subset-mset-abstract-red)
next
  case Lneg note L = this(1)

```

have $P \in ?N_{\mathcal{I}}$
using *not-d-interp unfolding* D *true-cls-def* L **by** (*auto split: if-split-asm*)
then obtain E **where**
 $DPN: E + \{\#Pos P\# \} \in N$ **and**
 $prod: production\ N\ (E + \{\#Pos P\# \}) = \{P\}$
using *in-interp-is-produced* **by** *blast*
have *sup-EC: superposition-rules* $(E + \{\#Pos P\# \})\ (C + \{\#Neg P\# \})\ (E + C)$
using *superposition-l* **by** *fast*
then have *superposition* $N\ (N \cup \{E+C\})$
using $DPN\ \langle D \in N \rangle$ *unfolding* $D\ L$ **by** (*auto simp add: superposition.simps*)
have
 $PMax: Pos\ P = MMax\ (E + \{\#Pos P\# \})$ **and**
 $count\ (E + \{\#Pos P\# \})\ (Pos\ P) \leq 1$ **and**
 $S\ (E + \{\#Pos P\# \}) = \{\#\}$ **and**
 $\neg interp\ N\ (E + \{\#Pos P\# \}) \models_h E + \{\#Pos P\# \}$
using *prod unfolding production-unfold* **by** *auto*
have $Neg\ P \notin \# E$
using *prod produces-imp-neg-notin-lits* **by** *force*
then have $\bigwedge y. y \in \# (E + \{\#Pos P\# \})$
 $\implies count\ (E + \{\#Pos P\# \})\ (Neg\ P) < count\ (C + \{\#Neg P\# \})\ (Neg\ P)$
using *count-greater-zero-iff* **by** *fastforce*
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 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 count-greater-zero-iff less-iff-Suc-add zero-less-Suc*)
have *ce-lt-d: $C + E \# \subset \# D$*
unfolding $D\ L$ **by** (*simp add: $(\bigwedge y. y \in \# E + \{\#Pos P\# \}) \implies y < Neg\ P$ ex-gt-imp-less-multiset*)
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 $D\ \langle P \in ground-resolution-with-selection.INTERP\ S\ N \rangle$
 $\langle count\ (E + \{\#Pos P\# \})\ (Pos\ P) \leq 1 \rangle$ *multi-member-skip not-d-interp*
by (*auto simp: not-in-iff*)
then have $\bigwedge y. y \in \# C+E$
 $\implies count\ (C+E)\ (Pos\ P) < count\ (E + \{\#Pos P\# \})\ (Pos\ P)$
using *set-mset-def* **by** *fastforce*

have $\neg redundant\ (C + E)\ N$
proof (*rule ccontr*)
assume $red'[simplified]: \neg ?thesis$
have $abs: clss-lt\ N\ (C + E) \models_p C + E$
using *redundant-iff-abstract red'* *unfolding abstract-red-def* **by** *auto*
have $clss-lt\ N\ (C + E) \models_p E + \{\#Pos P\# \} \vee clss-lt\ N\ (C + E) \models_p C + \{\#Neg P\# \}$
proof *clarify*
assume $CP: \neg clss-lt\ N\ (C + E) \models_p C + \{\#Neg P\# \}$
{ fix I
assume
 $total-over-m\ I\ (clss-lt\ N\ (C + E) \cup \{E + \{\#Pos P\# \}\})$ **and**
 $consistent-interp\ I$ **and**
 $I \models_s clss-lt\ N\ (C + E)$
then have $I \models C + E$

```

      using abs sorry
    moreover have  $\neg I \models C + \{\#Neg P\}$ 
      using CP unfolding true-clss-clss-def
      sorry
    ultimately have  $I \models E + \{\#Pos P\}$  by auto
  }
  then show  $clss\text{-}lt\ N\ (C + E) \models_p E + \{\#Pos P\}$ 
    unfolding true-clss-clss-def by auto
  qed
  moreover have  $clss\text{-}lt\ N\ (C + E) \subseteq clss\text{-}lt\ N\ (C + \{\#Neg P\})$ 
    using ce-lt-d mult-less-trans unfolding clss-lt-def D L by force
  ultimately have  $redundant\ (C + \{\#Neg P\})\ N \vee clss\text{-}lt\ N\ (C + E) \models_p E + \{\#Pos P\}$ 
    unfolding redundant-iff-abstract abstract-red-def using true-clss-clss-subset by blast
  show False sorry
  qed
  moreover have  $\neg redundant\ (E + \{\#Pos P\})\ N$ 
    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 asms unfolding abstract-red-def true-clss-clss-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  $A \in clss\text{-}lt\ N\ B$  using AN AB unfolding clss-lt-def
    by (auto dest: less-eq-imp-le-multiset simp add: multiset-order.dual-order.order-iff-strict)
  then show ?thesis
    using AB unfolding abstract-red-def true-clss-clss-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)
  then show ?case
    using subsumed-is-redundant[of A N B] unfolding abstract-red-def class-lt-def by auto
qed

```

```

lemma redundant-mono:
  redundant A N  $\implies$  A  $\subseteq$  # B  $\implies$  redundant B N
  apply (induction rule: redundant.induct)
  by (meson subset-mset.less-le-trans subsumption)

```

```

locale trac =
  selection S for S :: nat clause  $\Rightarrow$  nat clause
begin

```

```

end

```

```

end

```

4.3 Partial Clausal Logic

We here define decided literals (that will be used in both DPLL and CDCL) and the entailment corresponding to it.

```

theory Partial-Annotated-Clausal-Logic
imports Partial-Clausal-Logic

```

```

begin

```

4.3.1 Decided Literals

Definition

```

datatype ('v, 'mark) ann-lit =
  is-decided: Decided (lit-of: 'v literal) |
  is-proped: Propagated (lit-of: 'v literal) (mark-of: 'mark)

```

```

lemma ann-lit-list-induct[case-names Nil Decided Propagated]:
  assumes P [] and
   $\bigwedge L\ xs. P\ xs \implies P\ (\text{Decided } L\ \# xs)$  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-decided-ex-Decided:
  is-decided L  $\implies$  ( $\bigwedge K. L = \text{Decided } K \implies P$ )  $\implies$  P
  by (cases L) auto

```

```

type-synonym ('v, 'm) ann-lits = ('v, 'm) ann-lit list

```

```

definition lits-of :: ('a, 'b) ann-lit set  $\Rightarrow$  'a literal set where
  lits-of Ls = lit-of ' Ls

```

```

abbreviation lits-of-l :: ('a, 'b) ann-lits  $\Rightarrow$  'a literal set where

```

$lits\text{-}of\text{-}l\ Ls \equiv lits\text{-}of\ (set\ Ls)$

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

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

lemma $lits\text{-}of\text{-}l\text{-}Un[simp]$:
 $lits\text{-}of\ (l \cup l') = lits\text{-}of\ l \cup lits\text{-}of\ l'$
unfolding $lits\text{-}of\text{-}def$ **by** $auto$

lemma $finite\text{-}lits\text{-}of\text{-}def[simp]$:
 $finite\ (lits\text{-}of\text{-}l\ L)$
unfolding $lits\text{-}of\text{-}def$ **by** $auto$

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

abbreviation $unmark\text{-}s$ **where**
 $unmark\text{-}s\ M \equiv unmark\ 'M$

abbreviation $unmark\text{-}l$ **where**
 $unmark\text{-}l\ M \equiv unmark\text{-}s\ (set\ M)$

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

lemma $lits\text{-}of\text{-}l\text{-}empty\text{-}is\text{-}empty[iff]$:
 $lits\text{-}of\text{-}l\ M = \{\} \longleftrightarrow M = []$
by $(induct\ M)\ (auto\ simp:\ lits\text{-}of\text{-}def)$

Entailment

definition $true\text{-}annot :: ('a, 'm) ann\text{-}lits \Rightarrow 'a\ clause \Rightarrow bool$ (**infix** \models_a 49) **where**
 $I \models_a C \longleftrightarrow (lits\text{-}of\text{-}l\ I) \models C$

definition $true\text{-}annots :: ('a, 'm) ann\text{-}lits \Rightarrow 'a\ clauses \Rightarrow bool$ (**infix** \models_{as} 49) **where**
 $I \models_{as} CC \longleftrightarrow (\forall C \in CC. I \models_a C)$

lemma $true\text{-}annot\text{-}empty\text{-}model[simp]$:
 $\neg [] \models_a \psi$
unfolding $true\text{-}annot\text{-}def\ true\text{-}cls\text{-}def$ **by** $simp$

lemma $true\text{-}annot\text{-}empty[simp]$:
 $\neg I \models_a \{\#\}$
unfolding $true\text{-}annot\text{-}def\ true\text{-}cls\text{-}def$ **by** $simp$

lemma $empty\text{-}true\text{-}annots\text{-}def[iff]$:
 $[] \models_{as} \psi \longleftrightarrow \psi = \{\}$
unfolding $true\text{-}annots\text{-}def$ **by** $auto$

lemma $true\text{-}annots\text{-}empty[simp]$:

$I \models_{as} \{\}$
unfolding *true-annots-def* **by** *auto*

lemma *true-annots-single-true-annot*[*iff*]:
 $I \models_{as} \{C\} \longleftrightarrow I \models_a C$
unfolding *true-annots-def* **by** *auto*

lemma *true-annot-insert-l*[*simp*]:
 $M \models_a A \implies L \# M \models_a A$
unfolding *true-annot-def* **by** *auto*

lemma *true-annots-insert-l* [*simp*]:
 $M \models_{as} A \implies L \# M \models_{as} A$
unfolding *true-annots-def* **by** *auto*

lemma *true-annots-union*[*iff*]:
 $M \models_{as} A \cup B \longleftrightarrow (M \models_{as} A \wedge M \models_{as} B)$
unfolding *true-annots-def* **by** *auto*

lemma *true-annots-insert*[*iff*]:
 $M \models_{as} \text{insert } a \ A \longleftrightarrow (M \models_a a \wedge M \models_{as} A)$
unfolding *true-annots-def* **by** *auto*

Link between \models_{as} and \models_s :

lemma *true-annots-true-cls*:
 $I \models_{as} CC \longleftrightarrow \text{lits-of-l } I \models_s CC$
unfolding *true-annots-def* *Ball-def* *true-annot-def* *true-clss-def* **by** *auto*

lemma *in-lit-of-true-annot*:
 $a \in \text{lits-of-l } M \longleftrightarrow M \models_a \{\#a\# \}$
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*:
 $I \models_s \text{unmark-l } MLs \implies \text{lits-of-l } MLs \subseteq I$
unfolding *true-clss-def* *lits-of-def* **by** *auto*

lemma *true-annot-true-clss-cls*:
 $MLs \models_a \psi \implies \text{set } (\text{map } \text{unmark } MLs) \models_p \psi$
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*:
 $MLs \models_{as} \psi \implies \text{set } (\text{map } \text{unmark } MLs) \models_{ps} \psi$
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-clss-def)

lemma *true-annots-decided-true-cls*[*iff*]:
 $\text{map } \text{Decided } M \models_{as} N \longleftrightarrow \text{set } M \models_s N$
proof –

have *: *lit-of* ‘ *Decided* ‘ *set M = set M* **unfolding** *lits-of-def* **by** *force*
show ?*thesis* **by** (*simp add: true-annots-true-cls * lits-of-def*)
qed

lemma *true-annot-singleton[iff]*: $M \models_a \{\#L\# \} \longleftrightarrow L \in \text{lits-of-}l\ M$
unfolding *true-annot-def lits-of-def* **by** *auto*

lemma *true-annots-true-clss-clss*:
 $A \models_{as} \Psi \implies \text{unmark-}l\ A \models_{ps} \Psi$
unfolding *true-clss-clss-def true-annots-def true-clss-def*
by (*auto dest!: true-clss-singleton-lit-of-implies-incl*
simp: 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: true-annot-commute*)

lemma *true-annot-mono[dest]*:
 $\text{set } I \subseteq \text{set } I' \implies I \models_a N \implies I' \models_a N$
using *true-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*:
 $\text{set } I \subseteq \text{set } I' \implies I \models_{as} N \implies I' \models_{as} N$
unfolding *true-annots-def* **by** *auto*

Defined and undefined literals

We introduce the functions *defined-lit* and *undefined-lit* to know whether a literal is defined with respect to a list of decided literals (aka a trail in most cases).

Remark that *undefined* already exists and is a completely different Isabelle function.

definition *defined-lit* :: (*'a*, *'m*) *ann-lits* \Rightarrow *'a literal* \Rightarrow *bool*
where
 $\text{defined-lit } I\ L \longleftrightarrow (\text{Decided } L \in \text{set } I) \vee (\exists P. \text{Propagated } L\ P \in \text{set } I)$
 $\vee (\text{Decided } (-L) \in \text{set } I) \vee (\exists P. \text{Propagated } (-L)\ P \in \text{set } I)$

abbreviation *undefined-lit* :: (*'a*, *'m*) *ann-lits* \Rightarrow *'a literal* \Rightarrow *bool*
where $\text{undefined-lit } I\ L \equiv \neg \text{defined-lit } I\ L$

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

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

lemma *literal-is-lit-of-decided*:

assumes $L = \text{lit-of } x$
shows $(x = \text{Decided } L) \vee (\exists l'. x = \text{Propagated } L \ l')$
using *assms* **by** (*cases* x) *auto*

lemma *true-annot-iff-decided-or-true-lit*:

defined-lit $I \ L \longleftrightarrow (\text{lits-of-l } I \models L \vee \text{lits-of-l } I \models \neg L)$
unfolding *defined-lit-def* **by** (*auto simp add: lits-of-def rev-image-eqI dest!: literal-is-lit-of-decided*)

lemma *consistent-inter-true-annot-satisfiable*:

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

lemma *defined-lit-map*:

defined-lit $Ls \ L \longleftrightarrow \text{atm-of } L \in (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ ' set } Ls$
unfolding *defined-lit-def* **apply** (*rule iffI*)
using *image-iff* **apply** *fastforce*
by (*fastforce simp add: atm-of-eq-atm-of dest: atm-imp-decided-or-proped*)

lemma *defined-lit-uminus[iff]*:

defined-lit $I \ (-L) \longleftrightarrow \text{defined-lit } I \ L$
unfolding *defined-lit-def* **by** *auto*

lemma *Decided-Propagated-in-iff-in-lits-of-l*:

defined-lit $I \ L \longleftrightarrow (L \in \text{lits-of-l } I \vee \neg L \in \text{lits-of-l } I)$
unfolding *lits-of-def* **by** (*metis lits-of-def true-annot-iff-decided-or-true-lit true-lit-def*)

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

assumes
consistent-interp (*lits-of-l* Ls) **and**
undefined-lit $Ls \ L$
shows *consistent-interp* (*insert* L (*lits-of-l* Ls))
using *assms* **unfolding** *consistent-interp-def* **by** (*auto simp: Decided-Propagated-in-iff-in-lits-of-l*)

lemma *decided-empty[simp]*:

$\neg \text{defined-lit } [] \ L$
unfolding *defined-lit-def* **by** *simp*

4.3.2 Backtracking

fun *backtrack-split* :: $('v, 'm) \text{ ann-lits}$

$\Rightarrow ('v, 'm) \text{ ann-lits} \times ('v, 'm) \text{ ann-lits}$ **where**

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

backtrack-split (*Propagated* $L \ P \ \# \ \text{mlits}$) = *apfst* ((*op* $\#$) (*Propagated* $L \ P$)) (*backtrack-split* mlits) |

backtrack-split (*Decided* $L \ \# \ \text{mlits}$) = $([], \text{Decided } L \ \# \ \text{mlits})$

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

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

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

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

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

lemma *backtrack-split-list-eq[simp]*:

fst (backtrack-split l) @ (snd (backtrack-split l)) = l
by (induct l rule: ann-lit-list-induct) auto

lemma *backtrack-snd-empty-not-decided*:

backtrack-split M = (M'', []) $\implies \forall l \in \text{set } M. \neg \text{is-decided } l$
by (metis append-Nil2 backtrack-split-fst-not-decided backtrack-split-list-eq snd-conv)

lemma *backtrack-split-some-is-decided-then-snd-has-hd*:

$\exists l \in \text{set } M. \text{is-decided } l \implies \exists M' L' M''. \text{backtrack-split } M = (M'', L' \# M')$
by (metis backtrack-snd-empty-not-decided 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-decided) M, dropWhile (Not o is-decided) M)
by (induction M rule: ann-lit-list-induct) auto

4.3.3 Decomposition with respect to the First Decided Literals

In this section we define a function that returns a decomposition with the first decided literal. This function is useful to define the backtracking of DPLL.

Definition

The pattern *get-all-ann-decomposition* [] = [([], [])] is necessary otherwise, we can call the *hd* function in the other pattern.

fun *get-all-ann-decomposition* :: ('a, 'm) ann-lits
 $\Rightarrow ((\text{'a}, \text{'m}) \text{ ann-lits} \times (\text{'a}, \text{'m}) \text{ ann-lits}) \text{ list}$ **where**
get-all-ann-decomposition (Decided L # Ls) =
 (Decided L # Ls, []) # *get-all-ann-decomposition* Ls |
get-all-ann-decomposition (Propagated L P # Ls) =
 (apsnd ((op #) (Propagated L P)) (hd (*get-all-ann-decomposition* Ls)))
 # tl (*get-all-ann-decomposition* Ls) |
get-all-ann-decomposition [] = [([], [])]

value *get-all-ann-decomposition* [Propagated A5 B5, Decided C4, Propagated A3 B3,
 Propagated A2 B2, Decided C1, Propagated A0 B0]

Now we can prove several simple properties about the function.

lemma *get-all-ann-decomposition-never-empty[iff]*:

get-all-ann-decomposition M = [] \longleftrightarrow False
by (induct M, simp) (rename-tac a xs, case-tac a, auto)

lemma *get-all-ann-decomposition-never-empty-sym[iff]*:

[] = *get-all-ann-decomposition M \longleftrightarrow False*
using *get-all-ann-decomposition-never-empty[of M]* **by** presburger

lemma *get-all-ann-decomposition-decomp*:

hd (get-all-ann-decomposition S) = (a, c) $\implies S = c @ a$

proof (induct S arbitrary: a c)

case Nil

then show ?case **by** simp

next

case (Cons x A)

then show ?case **by** (cases x; cases hd (get-all-ann-decomposition A)) auto
qed

lemma get-all-ann-decomposition-backtrack-split:

backtrack-split $S = (M, M') \longleftrightarrow \text{hd } (\text{get-all-ann-decomposition } S) = (M', M)$

proof (induction S arbitrary: M M')

case Nil

then show ?case **by** auto

next

case (Cons a S)

then show ?case **using** backtrack-split-takeWhile-dropWhile **by** (cases a) force+

qed

lemma get-all-ann-decomposition-Nil-backtrack-split-snd-Nil:

get-all-ann-decomposition $S = [([], A)] \implies \text{snd } (\text{backtrack-split } S) = []$

by (simp add: get-all-ann-decomposition-backtrack-split sndI)

This functions says that the first element is either empty or starts with a decided element of the list.

lemma get-all-ann-decomposition-length-1-fst-empty-or-length-1:

assumes get-all-ann-decomposition $M = (a, b) \# []$

shows $a = [] \vee (\text{length } a = 1 \wedge \text{is-decided } (\text{hd } a) \wedge \text{hd } a \in \text{set } M)$

using assms

proof (induct M arbitrary: a b rule: ann-lit-list-induct)

case Nil **then show** ?case **by** simp

next

case (Decided L mark)

then show ?case **by** simp

next

case (Propagated L mark M)

then show ?case **by** (cases get-all-ann-decomposition M) force+

qed

lemma get-all-ann-decomposition-fst-empty-or-hd-in-M:

assumes get-all-ann-decomposition $M = (a, b) \# l$

shows $a = [] \vee (\text{is-decided } (\text{hd } a) \wedge \text{hd } a \in \text{set } M)$

using assms **apply** (induct M arbitrary: a b rule: ann-lit-list-induct)

apply auto[2]

by (metis UnCI backtrack-split-snd-hd-decided get-all-ann-decomposition-backtrack-split
get-all-ann-decomposition-decomp hd-in-set list.sel(1) set-append snd-conv)

lemma get-all-ann-decomposition-snd-not-decided:

assumes $(a, b) \in \text{set } (\text{get-all-ann-decomposition } M)$

and $L \in \text{set } b$

shows $\neg \text{is-decided } L$

using assms **apply** (induct M arbitrary: a b rule: ann-lit-list-induct, simp)

by (rename-tac L' xs a b, case-tac get-all-ann-decomposition xs; fastforce)+

lemma tl-get-all-ann-decomposition-skip-some:

assumes $x \in \text{set } (\text{tl } (\text{get-all-ann-decomposition } M1))$

shows $x \in \text{set } (\text{tl } (\text{get-all-ann-decomposition } (M0 @ M1)))$

using assms

by (induct M0 rule: ann-lit-list-induct)

(auto simp add: list.set-sel(2))

lemma hd-get-all-ann-decomposition-skip-some:

```

assumes (x, y) = hd (get-all-ann-decomposition M1)
shows (x, y) ∈ set (get-all-ann-decomposition (M0 @ Decided K # M1))
using assms
proof (induction M0 rule: ann-lit-list-induct)
  case Nil
  then show ?case by auto
next
  case (Decided L M0)
  then show ?case by auto
next
  case (Propagated L C M0) note xy = this(1)[OF this(2-)] and hd = this(2)
  then show ?case
    by (cases get-all-ann-decomposition (M0 @ Decided K # M1))
      (auto dest!: get-all-ann-decomposition-decomp
        arg-cong[of get-all-ann-decomposition - - hd])
qed

```

lemma *in-get-all-ann-decomposition-in-get-all-ann-decomposition-prepend:*
 $(a, b) \in \text{set } (\text{get-all-ann-decomposition } M') \implies$
 $\exists b'. (a, b' @ b) \in \text{set } (\text{get-all-ann-decomposition } (M @ M'))$
apply (induction M rule: ann-lit-list-induct)
apply (metis append-Nil)
apply auto[]
by (rename-tac L' m xs, case-tac get-all-ann-decomposition (xs @ M')) auto

lemma *in-get-all-ann-decomposition-decided-or-empty:*
assumes $(a, b) \in \text{set } (\text{get-all-ann-decomposition } M)$
shows $a = [] \vee (\text{is-decided } (\text{hd } a))$
using *assms*
proof (induct M arbitrary: a b rule: ann-lit-list-induct)
case Nil **then show** ?case **by** simp
next
case (Decided l M)
then show ?case **by** auto
next
case (Propagated l mark M)
then show ?case **by** (cases get-all-ann-decomposition M) force+
qed

lemma *get-all-ann-decomposition-remove-undecided-length:*
assumes $\forall l \in \text{set } M'. \neg \text{is-decided } l$
shows $\text{length } (\text{get-all-ann-decomposition } (M' @ M'')) = \text{length } (\text{get-all-ann-decomposition } M'')$
using *assms* **by** (induct M' arbitrary: M'' rule: ann-lit-list-induct) auto

lemma *get-all-ann-decomposition-not-is-decided-length:*
assumes $\forall l \in \text{set } M'. \neg \text{is-decided } l$
shows $1 + \text{length } (\text{get-all-ann-decomposition } (\text{Propagated } (-L) P \# M))$
 $= \text{length } (\text{get-all-ann-decomposition } (M' @ \text{Decided } L \# M))$
using *assms* *get-all-ann-decomposition-remove-undecided-length* **by** fastforce

lemma *get-all-ann-decomposition-last-choice:*
assumes $\text{tl } (\text{get-all-ann-decomposition } (M' @ \text{Decided } L \# M)) \neq []$
and $\forall l \in \text{set } M'. \neg \text{is-decided } l$
and $\text{hd } (\text{tl } (\text{get-all-ann-decomposition } (M' @ \text{Decided } L \# M))) = (M0', M0)$
shows $\text{hd } (\text{get-all-ann-decomposition } (\text{Propagated } (-L) P \# M)) = (M0', \text{Propagated } (-L) P \# M0)$
using *assms* **by** (induct M' rule: ann-lit-list-induct) auto

```

lemma get-all-ann-decomposition-except-last-choice-equal:
  assumes  $\forall l \in \text{set } M'. \neg \text{is-decided } l$ 
  shows  $tl \ (get-all-ann-decomposition \ (Propagated \ (-L) \ P \ \# \ M))$ 
   $= tl \ (tl \ (get-all-ann-decomposition \ (M' \ @ \ Decided \ L \ \# \ M)))$ 
  using assms by (induct  $M'$  rule: ann-lit-list-induct) auto

lemma get-all-ann-decomposition-hd-hd:
  assumes  $get-all-ann-decomposition \ Ls = (M, C) \ \# \ (M0, M0') \ \# \ l$ 
  shows  $tl \ M = M0' \ @ \ M0 \wedge \text{is-decided} \ (hd \ M)$ 
  using assms
proof (induct  $Ls$  arbitrary:  $M \ C \ M0 \ M0' \ l$ )
  case Nil
  then show ?case by simp
next
  case (Cons  $a \ Ls \ M \ C \ M0 \ M0' \ l$ ) note  $IH = \text{this}(1)$  and  $g = \text{this}(2)$ 
  { fix  $L \ \text{level}$ 
    assume  $a: a = Decided \ L$ 
    have  $Ls = M0' \ @ \ M0$ 
    using  $g \ a$  by (force intro: get-all-ann-decomposition-decomp)
    then have  $tl \ M = M0' \ @ \ M0 \wedge \text{is-decided} \ (hd \ M)$  using  $g \ a$  by auto
  }
  moreover {
    fix  $L \ P$ 
    assume  $a: a = Propagated \ L \ P$ 
    have  $tl \ M = M0' \ @ \ M0 \wedge \text{is-decided} \ (hd \ M)$ 
    using  $IH \ Cons.premis$  unfolding  $a$  by (cases get-all-ann-decomposition  $Ls$ ) auto
  }
  ultimately show ?case by (cases  $a$ ) auto
qed

lemma get-all-ann-decomposition-exists-prepend[dest]:
  assumes  $(a, b) \in \text{set} \ (get-all-ann-decomposition \ M)$ 
  shows  $\exists c. M = c \ @ \ b \ @ \ a$ 
  using assms apply (induct  $M$  rule: ann-lit-list-induct)
  apply simp
  by (rename-tac  $L' \ xs$ , case-tac get-all-ann-decomposition  $xs$ ;
    auto dest!: arg-cong[of get-all-ann-decomposition - - hd]
    get-all-ann-decomposition-decomp) +

lemma get-all-ann-decomposition-incl:
  assumes  $(a, b) \in \text{set} \ (get-all-ann-decomposition \ M)$ 
  shows  $\text{set } b \subseteq \text{set } M$  and  $\text{set } a \subseteq \text{set } M$ 
  using assms get-all-ann-decomposition-exists-prepend by fastforce +

lemma get-all-ann-decomposition-exists-prepend':
  assumes  $(a, b) \in \text{set} \ (get-all-ann-decomposition \ M)$ 
  obtains  $c$  where  $M = c \ @ \ b \ @ \ a$ 
  using assms apply (induct  $M$  rule: ann-lit-list-induct)
  apply auto[1]
  by (rename-tac  $L' \ xs$ , case-tac hd (get-all-ann-decomposition  $xs$ ),
    auto dest!: get-all-ann-decomposition-decomp simp add: list.set-sel(2)) +

lemma union-in-get-all-ann-decomposition-is-subset:
  assumes  $(a, b) \in \text{set} \ (get-all-ann-decomposition \ M)$ 
  shows  $\text{set } a \cup \text{set } b \subseteq \text{set } M$ 

```

using *assms* by *force*

lemma *Decided-cons-in-get-all-ann-decomposition-append-Decided-cons*:
 $\exists M1\ M2. (Decided\ K\ \# \ M1, M2) \in \text{set } (get\text{-all-ann-decomposition } (c\ @\ Decided\ K\ \# \ c'))$
apply (*induction* *c* *rule*: *ann-lit-list-induct*)
apply *auto*[2]
apply (*rename-tac* *L* *xs*,
case-tac *hd* (*get-all-ann-decomposition* (*xs* @ *Decided* *K* # *c'*)))
apply (*case-tac* *get-all-ann-decomposition* (*xs* @ *Decided* *K* # *c'*))
by *auto*

lemma *fst-get-all-ann-decomposition-prepend-not-decided*:
assumes $\forall m \in \text{set } MS. \neg \text{is-decided } m$
shows *set* (*map* *fst* (*get-all-ann-decomposition* *M*))
 $= \text{set } (\text{map } \text{fst } (\text{get-all-ann-decomposition } (MS\ @\ M)))$
using *assms* **apply** (*induction* *MS* *rule*: *ann-lit-list-induct*)
apply *auto*[2]
by (*rename-tac* *L* *m* *xs*; *case-tac* *get-all-ann-decomposition* (*xs* @ *M*)) *simp-all*

Entailment of the Propagated by the Decided Literal

lemma *get-all-ann-decomposition-snd-union*:
 $\text{set } M = \bigcup (\text{set } 'snd' \text{ set } (get\text{-all-ann-decomposition } M)) \cup \{L \mid L. \text{is-decided } L \wedge L \in \text{set } M\}$
(is *?M* *M* = *?U* *M* \cup *?Ls* *M*)
proof (*induct* *M* *rule*: *ann-lit-list-induct*)
case *Nil*
then show *?case* **by** *simp*
next
case (*Decided* *L* *M*) **note** *IH* = *this*(1)
then have *Decided* *L* \in *?Ls* (*Decided* *L* # *M*) **by** *auto*
moreover have *?U* (*Decided* *L* # *M*) = *?U* *M* **by** *auto*
moreover have *?M* *M* = *?U* *M* \cup *?Ls* *M* **using** *IH* **by** *auto*
ultimately show *?case* **by** *auto*
next
case (*Propagated* *L* *m* *M*)
then show *?case* **by** (*cases* (*get-all-ann-decomposition* *M*)) *auto*
qed

definition *all-decomposition-implies* :: 'a literal multiset set
 $\Rightarrow ((\text{'a}, \text{'m}) \text{ ann-lits} \times (\text{'a}, \text{'m}) \text{ ann-lits}) \text{ list} \Rightarrow \text{bool})$ **where**
all-decomposition-implies *N* *S* $\longleftrightarrow (\forall (Ls, \text{seen}) \in \text{set } S. \text{unmark-l } Ls \cup N \models_{ps} \text{unmark-l } \text{seen})$

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*)] $\longleftrightarrow \text{unmark-l } Ls \cup N \models_{ps} \text{unmark-l } \text{seen}$
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 (*all-decomposition-implies* N [(Ls , *seen*)] \wedge *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
 $(\text{unmark-}l \text{ (fst } l) \cup N \models_{ps} \text{unmark-}l \text{ (snd } l) \wedge$
 $\text{all-decomposition-implies } N S')$
unfolding *all-decomposition-implies-def* **by** *auto*

lemma *all-decomposition-implies-trail-is-implied*:
assumes *all-decomposition-implies* N (*get-all-ann-decomposition* M)
shows $N \cup \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } M\}$
 $\models_{ps} \text{unmark } ' \bigcup (\text{set } ' \text{snd } ' \text{set } (\text{get-all-ann-decomposition } M))$
using *assms*
proof (*induct length (get-all-ann-decomposition M) arbitrary: M*)
case 0
then show ?*case* **by** *auto*
next
case (*Suc n*) **note** $IH = \text{this}(1)$ **and** $\text{length} = \text{this}(2)$ **and** $\text{decomp} = \text{this}(3)$
consider
 $(le1) \text{length } (\text{get-all-ann-decomposition } M) \leq 1$
 $\mid (gt1) \text{length } (\text{get-all-ann-decomposition } M) > 1$
by *arith*
then show ?*case*
proof *cases*
case *le1*
then obtain a b **where** $g: \text{get-all-ann-decomposition } M = (a, b) \# []$
by (*cases get-all-ann-decomposition M*) *auto*
moreover {
assume $a = []$
then have ?*thesis* **using** *Suc.premis g* **by** *auto*
}
moreover {
assume $l: \text{length } a = 1$ **and** $m: \text{is-decided } (\text{hd } a)$ **and** $hd: \text{hd } a \in \text{set } M$
then have $\text{unmark } (\text{hd } a) \in \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } M\}$ **by** *auto*
then have $H: \text{unmark-}l \ a \cup N \subseteq N \cup \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } M\}$
using l **by** (*cases a*) *auto*
have $f1: \text{unmark-}l \ a \cup N \models_{ps} \text{unmark-}l \ b$
using *decomp* **unfolding** *all-decomposition-implies-def g* **by** *simp*
have ?*thesis*
apply (*rule true-clss-clss-subset*) **using** $f1 \ H \ g$ **by** *auto*
}
ultimately show ?*thesis*
using *get-all-ann-decomposition-length-1-fst-empty-or-length-1* **by** *blast*
next
case *gt1*
then obtain $Ls0$ $seen0$ M' **where**
 $Ls0: \text{get-all-ann-decomposition } M = (Ls0, \text{seen0}) \# \text{get-all-ann-decomposition } M'$ **and**
 $\text{length}' : \text{length } (\text{get-all-ann-decomposition } M') = n$ **and**
 $M'\text{-in-}M: \text{set } M' \subseteq \text{set } M$
using length **by** (*induct M rule: ann-lit-list-induct*) (*auto simp: subset-insertI2*)
let ? $d = \bigcup (\text{set } ' \text{snd } ' \text{set } (\text{get-all-ann-decomposition } M'))$
let ? $unM = \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } M\}$
let ? $unM' = \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } M'\}$
{
assume $n = 0$

```

then have get-all-ann-decomposition  $M' = []$  using length' by auto
then have ?thesis using Suc.prems unfolding all-decomposition-implies-def Ls0 by auto
}
moreover {
  assume  $n: n > 0$ 
  then obtain  $Ls1$  seen1  $l$  where
     $Ls1$ : get-all-ann-decomposition  $M' = (Ls1, seen1) \# l$ 
    using length' by (induct  $M'$  rule: ann-lit-list-induct) auto

  have all-decomposition-implies  $N$  (get-all-ann-decomposition  $M'$ )
    using decomp unfolding  $Ls0$  by auto
  then have  $N: N \cup ?unM' \models_{ps} unmark-s ?d$ 
    using IH length' by auto
  have  $l: N \cup ?unM' \subseteq N \cup ?unM$ 
    using M'-in-M by auto
  from true-clss-clss-subset[OF this N]
  have  $\Psi N: N \cup ?unM \models_{ps} unmark-s ?d$  by auto
  have is-decided (hd  $Ls0$ ) and  $LS: tl\ Ls0 = seen1 \ @\ Ls1$ 
    using get-all-ann-decomposition-hd-hd[of M] unfolding  $Ls0\ Ls1$  by auto

  have  $LSM: seen1 \ @\ Ls1 = M'$  using get-all-ann-decomposition-decomp[of M]  $Ls1$  by auto
  have  $M'$ : set  $M' = ?d \cup \{L \mid L. is-decided\ L \wedge L \in set\ M'\}$ 
    using get-all-ann-decomposition-snd-union by auto

  {
    assume  $Ls0 \neq []$ 
    then have hd  $Ls0 \in set\ M$ 
      using get-all-ann-decomposition-fst-empty-or-hd-in-M  $Ls0$  by blast
    then have  $N \cup ?unM \models_p unmark\ (hd\ Ls0)$ 
      using  $\langle is-decided\ (hd\ Ls0) \rangle$  by (metis (mono-tags, lifting) UnCI mem-Collect-eq true-clss-clss-in)
  } note hd-Ls0 = this

  have  $l: unmark\ '(\ ?d \cup \{L \mid L. is-decided\ L \wedge L \in set\ M'\}) = unmark-s\ ?d \cup ?unM'$ 
    by auto
  have  $N \cup ?unM' \models_{ps} unmark\ '(\ ?d \cup \{L \mid L. is-decided\ L \wedge L \in set\ M'\})$ 
    unfolding  $l$  using  $N$  by (auto simp: all-in-true-clss-clss)
  then have  $t: N \cup ?unM' \models_{ps} unmark-l\ (tl\ Ls0)$ 
    using  $M'$  unfolding  $LS\ LSM$  by auto
  then have  $N \cup ?unM \models_{ps} unmark-l\ (tl\ Ls0)$ 
    using M'-in-M true-clss-clss-subset[OF - t, of N  $\cup$  ?unM] by auto
  then have  $N \cup ?unM \models_{ps} unmark-l\ Ls0$ 
    using hd-Ls0 by (cases  $Ls0$ ) auto

  moreover have  $unmark-l\ Ls0 \cup N \models_{ps} unmark-l\ seen0$ 
    using decomp unfolding  $Ls0$  by simp
  moreover have  $\bigwedge M\ Ma. (M::'a\ literal\ multiset\ set) \cup Ma \models_{ps} M$ 
    by (simp add: all-in-true-clss-clss)
  ultimately have  $\Psi: N \cup ?unM \models_{ps} unmark-l\ seen0$ 
    by (meson true-clss-clss-left-right true-clss-clss-union-and true-clss-clss-union-l-r)

  moreover have  $unmark\ '(\ set\ seen0 \cup ?d) = unmark-l\ seen0 \cup unmark-s\ ?d$ 
    by auto
  ultimately have ?thesis using  $\Psi N$  unfolding  $Ls0$  by simp
}
ultimately show ?thesis by auto

```

qed
qed

lemma *all-decomposition-implies-propagated-lits-are-implied*:
assumes *all-decomposition-implies* N (*get-all-ann-decomposition* M)
shows $N \cup \{\text{unmark } L \mid L. \text{ is-decided } L \wedge L \in \text{set } M\} \models_{ps} \text{unmark-l } M$
(is $?I \models_{ps} ?A$)

proof –

have $?I \models_{ps} \text{unmark-s } \{L \mid L. \text{ is-decided } L \wedge L \in \text{set } M\}$
by (*auto intro: all-in-true-clss-clss*)
moreover have $?I \models_{ps} \text{unmark } ' \bigcup (\text{set } ' \text{snd } ' \text{set } (\text{get-all-ann-decomposition } M))$
using *all-decomposition-implies-trail-is-implied* **assms** **by** *blast*
ultimately have $N \cup \{\text{unmark } m \mid m. \text{ is-decided } m \wedge m \in \text{set } M\}$
 $\models_{ps} \text{unmark } ' \bigcup (\text{set } ' \text{snd } ' \text{set } (\text{get-all-ann-decomposition } M))$
 $\cup \text{unmark } ' \{m \mid m. \text{ is-decided } m \wedge m \in \text{set } M\}$
by *blast*
then show $?thesis$
by (*metis (no-types) get-all-ann-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*

4.3.4 Negation of Clauses

We define the negation of a *'a Partial-Clausal-Logic.clause*: it converts it from the a single clause to a set of clauses, wherein each clause is a single negated literal.

definition $CNot :: 'v \text{ clause} \Rightarrow 'v \text{ clauses}$ **where**
 $CNot \ \psi = \{ \{ \# - L \# \} \mid L. L \in \# \ \psi \}$

lemma *in-CNot-uminus[iff]*:
shows $\{ \# L \# \} \in CNot \ \psi \longleftrightarrow -L \in \# \ \psi$
unfolding *CNot-def* **by** *force*

lemma
shows
CNot-singleton[simp]: $CNot \ \{ \# L \# \} = \{ \{ \# - L \# \} \}$ **and**
CNot-empty[simp]: $CNot \ \{ \# \} = \{ \}$ **and**
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** $-L \in \text{lits-of-l } M$
using *assms* **by** (*auto simp: true-annots-def true-annot-def CNot-def*)

lemma *CNot-remdups-mset[simp]*:
 $CNot \ (\text{remdups-mset } A) = CNot \ A$
unfolding *CNot-def* **by** *auto*

lemma *Ball-CNot-Ball-mset[simp]*:
 $(\forall x \in CNot\ D. P\ x) \longleftrightarrow (\forall L \in \#\ D. P\ \{\#-L\# \})$
unfolding *CNot-def* **by** *auto*

lemma *consistent-CNot-not*:
assumes *consistent-interp I*
shows $I \models_s CNot\ \varphi \implies \neg I \models \varphi$
using *assms unfolding consistent-interp-def true-clss-def true-cls-def* **by** *auto*

lemma *total-not-true-cls-true-clss-CNot*:
assumes *total-over-m I {φ}* **and** $\neg I \models \varphi$
shows $I \models_s CNot\ \varphi$
using *assms unfolding total-over-m-def total-over-set-def true-clss-def true-cls-def CNot-def*
apply *clarify*
by *(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 {φ}* **and** $\neg I \models_s CNot\ \varphi$
shows $I \models \varphi$
using *assms total-not-true-cls-true-clss-CNot* **by** *auto*

lemma *atms-of-ms-CNot-atms-of[simp]*:
 $atms-of-ms\ (CNot\ C) = atms-of\ C$
unfolding *atms-of-ms-def atms-of-def CNot-def* **by** *fastforce*

lemma *true-clss-clss-contradiction-true-clss-cls-false*:
 $C \in D \implies D \models_{ps} CNot\ C \implies D \models_p \{\#\}$
unfolding *true-clss-clss-def true-clss-cls-def total-over-m-def*
by *(metis Un-commute atms-of-empty atms-of-ms-CNot-atms-of atms-of-ms-insert atms-of-ms-union consistent-CNot-not insert-absorb sup-bot.left-neutral true-clss-def)*

lemma *true-annots-CNot-all-atms-defined*:
assumes $M \models_{as} CNot\ T$ **and** $a1: L \in \#\ T$
shows $atm-of\ L \in atm-of\ \text{'lits-of-l}\ M$
by *(metis assms atm-of-uminus image-eqI in-CNot-implies-uminus(1) true-annot-singleton)*

lemma *true-annots-CNot-all-uminus-atms-defined*:
assumes $M \models_{as} CNot\ T$ **and** $a1: -L \in \#\ T$
shows $atm-of\ L \in atm-of\ \text{'lits-of-l}\ M$
by *(metis assms atm-of-uminus image-eqI in-CNot-implies-uminus(1) true-annot-singleton)*

lemma *true-clss-clss-false-left-right*:
assumes $\{\{\#L\#\}\} \cup B \models_p \{\#\}$
shows $B \models_{ps} CNot\ \{\#L\#\}$
unfolding *true-clss-clss-def true-clss-cls-def*
proof *(intro allI impI)*
fix I
assume
 $tot: total-over-m\ I\ (B \cup CNot\ \{\#L\#\})$ **and**
 $cons: consistent-interp\ I$
 $I: I \models_s B$
have $total-over-m\ I\ (\{\{\#L\#\}\} \cup B)$ **using** *tot* **by** *auto*
then have $\neg I \models_s insert\ \{\#L\#\}\ B$
using *assms cons unfolding true-clss-cls-def* **by** *simp*
then show $I \models_s CNot\ \{\#L\#\}$
using *tot I* **by** *(cases L) auto*

qed

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

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

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

lemma *true-annot-CNot-diff:*

$I \models_{as} CNot\ C \implies I \models_{as} CNot\ (C - C')$

by (*auto simp: true-annots-true-cls-def-iff-negation-in-model dest: in-diffD*)

lemma *CNot-mset-replicate[simp]:*

$CNot\ (mset\ (replicate\ n\ L)) = (if\ n = 0\ then\ \{\}\ else\ \{\{\#-L\#\}\})$

by (*induction n*) *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-toal-over-m[simp]:*

$total_over_m\ I\ (CNot\ C) = total_over_set\ I\ (atms_of\ C)$

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

The following lemma is very useful when in the goal appears an axioms like $\neg L = K$: this lemma allows the simplifier to rewrite L.

lemma *uminus-lit-swap: $\neg(a::'a\ literal) = i \longleftrightarrow a = \neg i$*

by *auto*

lemma *true-clss-cls-plus-CNot:*

assumes

$CC-L: A \models_p CC + \{\#L\#\}$ **and**

$CNot-CC: A \models_{ps} CNot\ CC$

shows $A \models_p \{\#L\#\}$

unfolding *true-clss-clss-def true-clss-cls-def CNot-def total-over-m-def*

proof (*intro allI impI*)

fix *I*

assume

$tot: total_over_set\ I\ (atms_of_ms\ (A \cup \{\{\#L\#\}\}))$ **and**

$cons: consistent_interp\ I$ **and**

$I: I \models_s A$

let $?I = I \cup \{Pos\ P \mid P. P \in atms_of\ CC \wedge P \notin atm_of\ 'I\}$

have $cons': consistent_interp\ ?I$

using *cons unfolding consistent-interp-def*

by (*auto simp: uminus-lit-swap atms-of-def rev-image-eqI*)

have $I': ?I \models_s A$

using *I true-clss-union-increase* **by** *blast*

have $tot-CNot: total_over_m\ ?I\ (A \cup CNot\ CC)$

using *tot atms-of-s-def* **by** (*fastforce simp: total-over-m-def total-over-set-def*)

then have $tot-I-A-CC-L: total_over_m\ ?I\ (A \cup \{CC + \{\#L\#\}\})$

using *tot unfolding total-over-m-def total-over-set-atm-of* **by** *auto*

then have $?I \models CC + \{\#L\#\}$ **using** *CC-L cons' I' unfolding true-clss-cls-def* **by** *blast*

moreover
 have $?I \models_s CNot\ CC$ **using** $CNot\text{-}CC\ cons' I' tot\text{-}CNot$ **unfolding** $true\text{-}clss\text{-}clss\text{-}def$ **by** $auto$
 then have $\neg A \models_p CC$
 by $(metis\ (no\text{-}types,\ lifting)\ I'\ atm\text{-}of\text{-}ms\text{-}CNot\text{-}atms\text{-}of\text{-}ms\ atm\text{-}of\text{-}ms\text{-}union\ cons'\ consistent\text{-}CNot\text{-}not\ tot\text{-}CNot\ total\text{-}over\text{-}m\text{-}def\ true\text{-}clss\text{-}cls\text{-}def)$
 then have $\neg ?I \models CC$ **using** $\langle ?I \models_s CNot\ CC \rangle\ cons'\ consistent\text{-}CNot\text{-}not$ **by** $blast$
 ultimately have $?I \models \{\#L\# \}$ **by** $blast$
 then show $I \models \{\#L\# \}$
 by $(metis\ (no\text{-}types,\ lifting)\ atm\text{-}of\text{-}ms\text{-}union\ cons'\ consistent\text{-}CNot\text{-}not\ tot\ total\text{-}not\text{-}CNot\ total\text{-}over\text{-}m\text{-}def\ total\text{-}over\text{-}set\text{-}union\ true\text{-}clss\text{-}union\text{-}increase)$
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 $H: \forall x. x \in CNot\ A \longrightarrow L \# M \models_a x$ **and** $l: l \in CNot\ A$
 then have $L \# M \models_a l$ **by** $auto$
 then show $M \models_a l$ **using** $LA\ l$ **by** $(cases\ L)\ (auto\ simp: CNot\text{-}def)$
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** $atm\text{-}of\ (lit\text{-}of\ a) \notin atm\text{-}of\ D$
 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** $\forall x \in atm\text{-}of\ D. x \notin atm\text{-}of\ \text{'lits-of-l}\ M$
 shows $M' \models_a D$
using $assms$ **by** $(induct\ M)\ (auto\ dest: true\text{-}annot\text{-}remove\text{-}hd\text{-}if\text{-}notin\text{-}vars)$

lemma $true\text{-}annots\text{-}remove\text{-}if\text{-}notin\text{-}vars$:
 assumes $M @ M' \models_{as} D$ **and** $\forall x \in atm\text{-}of\text{-}ms\ D. x \notin atm\text{-}of\ \text{'lits-of-l}\ M$
 shows $M' \models_{as} D$ **unfolding** $true\text{-}annots\text{-}def$
using $assms$ **unfolding** $true\text{-}annots\text{-}def\ atm\text{-}of\text{-}ms\text{-}def$
by $(force\ dest: true\text{-}annot\text{-}remove\text{-}if\text{-}notin\text{-}vars)$

lemma $all\text{-}variables\text{-}defined\text{-}not\text{-}imply\text{-}cnot$:
 assumes
 $\forall s \in atm\text{-}of\text{-}ms\ \{B\}. s \in atm\text{-}of\ \text{'lits-of-l}\ A$ **and**
 $\neg A \models_a B$
 shows $A \models_{as} CNot\ B$
unfolding $true\text{-}annot\text{-}def\ true\text{-}annots\text{-}def\ Ball\text{-}def\ CNot\text{-}def\ true\text{-}lit\text{-}def$
proof $(clarify,\ rule\ ccontr)$
 fix L
 assume $LB: L \in \# B$ **and** $\neg lits\text{-}of\text{-}l\ A \models_l \neg L$
 then have $atm\text{-}of\ L \in atm\text{-}of\ \text{'lits-of-l}\ A$
using $assms(1)$ **by** $(simp\ add: atm\text{-}of\text{-}lit\text{-}in\text{-}atms\text{-}of\ lits\text{-}of\text{-}l\text{-}def)$
 then have $L \in lits\text{-}of\text{-}l\ A \vee \neg L \in lits\text{-}of\text{-}l\ A$

using *atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set* by *metis*
 then have $L \in \text{ lits-of-l } A$ using $\langle \neg \text{ lits-of-l } A \models l - L \rangle$ by *auto*
 then show *False*
 using *LB assms(2)* unfolding *true-annot-def true-lit-def true-cls-def Bex-def*
 by *blast*
 qed

lemma *CNot-union-mset[simp]*:
 $CNot (A \# \cup B) = CNot A \cup CNot B$
 unfolding *CNot-def* by *auto*

4.3.5 Other

abbreviation *no-dup* $L \equiv \text{ distinct } (\text{ map } (\lambda l. \text{ atm-of } (\text{ lit-of } l)) L)$

lemma *no-dup-rev[simp]*:
 $\text{ no-dup } (\text{ rev } M) \longleftrightarrow \text{ no-dup } M$
 by (*auto simp: rev-map[symmetric]*)

lemma *no-dup-length-eq-card-atm-of-lits-of-l*:
 assumes *no-dup* M
 shows $\text{ length } M = \text{ card } (\text{ atm-of } ' \text{ lits-of-l } M)$
 using *assms* unfolding *lits-of-def* by (*induct M*) (*auto simp add: image-image*)

lemma *distinct-consistent-interp*:
 $\text{ no-dup } M \implies \text{ consistent-interp } (\text{ lits-of-l } M)$

proof (*induct M*)

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

next

case (*Cons L M*)
 then have *a1*: *consistent-interp* (*lits-of-l M*) by *auto*
 have *a2*: $\text{ atm-of } (\text{ lit-of } L) \notin (\lambda l. \text{ atm-of } (\text{ lit-of } l)) ' \text{ set } M$ using *Cons.prem*s by *auto*
 have *undefined-lit M* (*lit-of L*)
 using *a2* unfolding *defined-lit-map* by *fastforce*
 then show *?case*
 using *a1* by *simp*

qed

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

lemma *true-annot-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 $\forall l \in \# A. \neg l \in \text{ lits-of-l } (L \# M)$
 using *assms(1)* *in-CNot-implies-uminus(2)* by *blast*

moreover

have $\text{ atm-of } (\text{ lit-of } L) \notin \text{ atm-of } ' \text{ lits-of-l } M$
 using *assms(3)* unfolding *lits-of-def* by *force*

then have $\text{lit-of } L \notin \text{lits-of-l } M$ **unfolding** *lits-of-def*
by (*metis (no-types) atm-of-uminus imageI*)
ultimately have $\forall l \in \# A. \neg l \in \text{lits-of-l } M$
using *assms(2)* **by** (*metis insert-iff list.simps(15) lits-of-insert uminus-of-uminus-id*)
then show *?thesis* **by** (*auto simp add: true-annots-def*)
qed

4.3.6 Extending Entailments to multisets

We have defined previous entailment with respect to sets, but we also need a multiset version depending on the context. The conversion is simple using the function *set-mset* (in this direction, there is no loss of information).

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*:: $'v \text{ clause multiset} \Rightarrow 'v \text{ clause multiset} \Rightarrow \text{bool}$ (**infix** \models_{psm} 50) **where**
 $I \models_{psm} C \equiv \text{set-mset } I \models_{ps} (\text{set-mset } C)$

Analog of theorem *true-clss-clss-subsetE*

lemma *true-clss-clss-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*:: $'a \text{ clause multiset} \Rightarrow 'a \text{ clause} \Rightarrow \text{bool}$ (**infix** \models_{pm} 50) **where**
 $I \models_{pm} C \equiv \text{set-mset } I \models_p C$

abbreviation *distinct-mset-mset* :: $'a \text{ multiset multiset} \Rightarrow \text{bool}$ **where**
 $\text{distinct-mset-mset } \Sigma \equiv \text{distinct-mset-set } (\text{set-mset } \Sigma)$

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

abbreviation *atms-of-mm* :: $'a \text{ literal multiset multiset} \Rightarrow 'a \text{ set}$ **where**
 $\text{atms-of-mm } U \equiv \text{atms-of-ms } (\text{set-mset } U)$

Other definition using *Union-mset*

lemma *atms-of-mm* $U \equiv \text{set-mset } (\bigcup \# \text{ image-mset } (\text{image-mset } \text{atm-of}) U)$
unfolding *atms-of-ms-def* **by** (*auto simp: atms-of-def*)

abbreviation *true-clss-m*:: $'a \text{ interp} \Rightarrow 'a \text{ clause multiset} \Rightarrow \text{bool}$ (**infix** \models_{sm} 50) **where**
 $I \models_{sm} C \equiv I \models_s \text{set-mset } C$

abbreviation *true-clss-ext-m* (**infix** \models_{sextm} 49) **where**
 $I \models_{sextm} C \equiv I \models_{sext} \text{set-mset } C$

type-synonym $'v \text{ clauses} = 'v \text{ clause multiset}$
end

Chapter 5

NOT's CDCL and DPLL

```
theory CDCL-WNOT-Measure
imports Main List-More
begin
```

The organisation of the development is the following:

- `CDCL_WNOT_Measure.thy` contains the measure used to show the termination the core of CDCL.
- `CDCL_NOT.thy` contains the specification of the rules: the rules are defined, and we proof the correctness and termination for some strategies CDCL.
- `DPLL_NOT.thy` contains the DPLL calculus based on the CDCL version.
- `DPLL_W.thy` contains Weidenbach's version of DPLL and the proof of equivalence between the two DPLL versions.

5.1 Measure

This measure show the termination of the core of CDCL: each step improves the number of literals we know for sure.

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**
 $\mu_C s b M \equiv (\sum i=0..<length M. M!i * b^{\wedge} (s + i - length M))$

lemma $\mu_C\text{-Nil}[simp]$:
 $\mu_C s b [] = 0$
unfolding $\mu_C\text{-def}$ **by** *auto*

lemma $\mu_C\text{-single}[simp]$:
 $\mu_C s b [L] = L * b^{\wedge} (s - Suc 0)$
unfolding $\mu_C\text{-def}$ **by** *auto*

lemma *set-sum-atLeastLessThan-add*:
 $(\sum i=k..<k+(b::nat). f i) = (\sum i=0..<b. f (k + i))$
by (*induction b*) *auto*

lemma *set-sum-atLeastLessThan-Suc*:

$(\sum i=1..< \text{Suc } j. f \ i) = (\sum i=0..< j. f \ (\text{Suc } i))$
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 –

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*

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*

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 {

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*

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

by *auto*

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 –

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*

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

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*)

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

unfolding μ_C -*def* **by** *auto*

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 {

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*

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 -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* μ_C -cons)

Copy of `~~/src/HOL/ex/NatSum.thy` (but generalized to $0 \leq k$)

lemma *sum-of-powers*: $0 \leq k \implies (k - 1) * (\sum_{i=0..<n. k^\wedge i} = k^\wedge n - (1::nat)$
apply (*cases* $k = 0$)
apply (*cases* n ; *simp*)
by (*induct* n) (*auto simp: Nat.nat-distrib*)

In the degenerated cases, we only have the large inequality holds. In the other cases, the following strict inequality holds:

lemma μ_C -bounded-non-degenerated:
fixes $b :: nat$
assumes
 $b > 0$ **and**
 $M \neq []$ **and**
 M -le: $\forall i < \text{length } M. M!i < b$ **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 -le **by** *auto*
then have $\mu_C s b M = 0$ **unfolding** μ_C -def **by** *auto*
then show *?thesis* **using** $\langle b > 0 \rangle$ **by** *auto*

next

case b

have $\forall i \in \{0..<\text{length } M\}. M!i * b^\wedge (s + i - \text{length } M) \leq (b-1) * b^\wedge (s + i - \text{length } M)$
using M -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** μ_C -def **by** (*auto intro: setsum-mono*)

also

have $\forall i \in \{0..<\text{length } M\}. (b-1) * b^\wedge (s + i - \text{length } M) = (b-1) * b^\wedge i * b^\wedge (s - \text{length } M)$
by (*metis* *Nat.add-diff-assoc2* *add.commute* *assms(4)* *mult.assoc* *power-add*)

then have $(\sum_{i=0..<\text{length } M. (b-1) * b^\wedge (s + i - \text{length } M))$
 $= (\sum_{i=0..<\text{length } M. (b-1) * b^\wedge i * b^\wedge (s - \text{length } M))$
by (*auto simp add: ac-simps*)

also have $\dots = (\sum_{i=0..<\text{length } M. b^\wedge i) * b^\wedge (s - \text{length } M) * (b-1)$
by (*simp add: setsum-left-distrib setsum-right-distrib ac-simps*)

finally have $\mu_C s b M \leq (\sum_{i=0..<\text{length } M. b^\wedge i) * (b-1) * b^\wedge (s - \text{length } M)$
by (*simp add: ac-simps*)

also

have $(\sum_{i=0..<\text{length } M. b^\wedge i) * (b-1) = b^\wedge (\text{length } M) - 1$
using *sum-of-powers*[*of* b $\text{length } M$] $\langle b > 1 \rangle$
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 <b>1> by auto
  also have ... = b ^ s
    by (metis assms(4) 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:  $\forall i < \text{length } M. M!i < b$  and
    s  $\geq \text{length } M$ 
    b > 0
  shows  $\mu_C \ s \ b \ M < b \wedge s$ 
proof -
  consider (M0)  $M = [] \mid (M) \ b > 0$  and  $M \neq []$ 
  using M-le by (cases b, cases M) auto
  then show ?thesis
  proof cases
    case M0
    then show ?thesis using M-le <b > 0> by auto
  next
    case M
    show ?thesis using  $\mu_C$ -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  $(\sum i=0..<n. M ! i * (0::nat) ^ i) \leq M ! 0$ 
        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

```

```

lemma finite-bounded-pair-list:
  fixes b :: nat
  shows finite { (ys, xs). length xs < s  $\wedge$  length ys < s  $\wedge$ 
    ( $\forall i < \text{length } xs. xs ! i < b$ )  $\wedge$  ( $\forall i < \text{length } ys. ys ! i < b$ ) }

```

proof –

have $H: \{(ys, xs). \text{length } xs < s \wedge \text{length } ys < s \wedge$
 $(\forall i < \text{length } xs. xs ! i < b) \wedge (\forall i < \text{length } ys. ys ! i < b)\}$
 \subseteq
 $\{xs. \text{length } xs < s \wedge (\forall i < \text{length } xs. xs ! i < b)\} \times$
 $\{xs. \text{length } xs < s \wedge (\forall i < \text{length } xs. xs ! i < b)\}$
by *auto*
moreover have *finite* $\{xs. \text{length } xs < s \wedge (\forall i < \text{length } xs. xs ! i < b)\}$
by (*rule finite-bounded-list*)
ultimately show *?thesis* **by** (*auto simp: finite-subset*)

qed

definition $\nu NOT :: nat \Rightarrow nat \Rightarrow (nat \text{ list} \times nat \text{ list}) \text{ set}$ **where**
 $\nu NOT \ s \ base = \{(ys, xs). \text{length } xs < s \wedge \text{length } ys < s \wedge$
 $(\forall i < \text{length } xs. xs ! i < base) \wedge (\forall i < \text{length } ys. ys ! i < base) \wedge$
 $(ys, xs) \in \text{lenlex less-than}\}$

lemma *finite- νNOT* [*simp*]:

finite ($\nu NOT \ s \ base$)

proof –

have $\nu NOT \ s \ base \subseteq \{(ys, xs). \text{length } xs < s \wedge \text{length } ys < s \wedge$
 $(\forall i < \text{length } xs. xs ! i < base) \wedge (\forall i < \text{length } ys. ys ! i < base)\}$
by (*auto simp: νNOT -def*)
moreover have *finite* $\{(ys, xs). \text{length } xs < s \wedge \text{length } ys < s \wedge$
 $(\forall i < \text{length } xs. xs ! i < base) \wedge (\forall i < \text{length } ys. ys ! i < base)\}$
by (*rule finite-bounded-pair-list*)
ultimately show *?thesis* **by** (*auto simp: finite-subset*)

qed

lemma *acyclic- νNOT* : *acyclic* ($\nu NOT \ s \ base$)

apply (*rule acyclic-subset*[*of lenlex less-than $\nu NOT \ s \ base$*])

apply (*rule wf-acyclic*)

by (*auto simp: νNOT -def*)

lemma *wf- νNOT* : *wf* ($\nu NOT \ s \ base$)

by (*rule finite-acyclic-wf*) (*auto simp: acyclic- νNOT*)

end

theory *CDCL-NOT*

imports *List-More Wellfounded-More CDCL-WNOT-Measure Partial-Annotated-Clausal-Logic*

begin

5.2 NOT's CDCL

5.2.1 Auxiliary Lemmas and Measure

We define here some more simplification rules, or rules that have been useful as help for some tactic

lemma *no-dup-cannot-not-lit-and-uminus*:

$\text{no-dup } M \Longrightarrow \text{lit-of } xa = \text{lit-of } x \Longrightarrow x \in \text{set } M \Longrightarrow xa \notin \text{set } M$

by (*metis atm-of-uminus distinct-map inj-on-eq-iff uminus-not-id'*)

lemma *atms-of-ms-single-atm-of*[*simp*]:

$\text{atms-of-ms } \{\text{unmark } L \mid L. P \ L\} = \text{atm-of } \{\text{lit-of } L \mid L. P \ L\}$

unfolding *atms-of-ms-def* **by** *force*

lemma *atms-of-uminus-lit-atm-of-lit-of*:
 $atms-of \{ \# - lit-of x. x \in \# A \# \} = atm-of ' (lit-of ' (set-mset A))$
unfolding *atms-of-def* **by** (auto simp add: Fun.image-comp)

lemma *atms-of-ms-single-image-atm-of-lit-of*:
 $atms-of-ms (unmark-s A) = atm-of ' (lit-of ' A)$
unfolding *atms-of-ms-def* **by** auto

5.2.2 Initial definitions

The state

We define here an abstraction over operation on the state we are manipulating.

locale *dp11-state-ops* =
fixes
 $trail :: 'st \Rightarrow ('v, unit) \text{ ann-lits}$ **and**
 $clauses_{NOT} :: 'st \Rightarrow 'v \text{ clauses}$ **and**
 $prepend-trail :: ('v, unit) \text{ ann-lit} \Rightarrow 'st \Rightarrow 'st$ **and**
 $tl-trail :: 'st \Rightarrow 'st$ **and**
 $add-cls_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$ **and**
 $remove-cls_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$
begin
abbreviation $state_{NOT} :: 'st \Rightarrow ('v, unit) \text{ ann-lit list} \times 'v \text{ clauses}$ **where**
 $state_{NOT} S \equiv (trail S, clauses_{NOT} S)$
end

NOT's state is basically a pair composed of the trail (i.e. the candidate model) and the set of clauses. We abstract this state to convert this state to other states. like Weidenbach's five-tuple.

locale *dp11-state* =
dp11-state-ops
 $trail \ clauses_{NOT} \ prepend-trail \ tl-trail \ add-cls_{NOT} \ remove-cls_{NOT}$ — related to the state
for
 $trail :: 'st \Rightarrow ('v, unit) \text{ ann-lits}$ **and**
 $clauses_{NOT} :: 'st \Rightarrow 'v \text{ clauses}$ **and**
 $prepend-trail :: ('v, unit) \text{ ann-lit} \Rightarrow 'st \Rightarrow 'st$ **and**
 $tl-trail :: 'st \Rightarrow 'st$ **and**
 $add-cls_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$ **and**
 $remove-cls_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$ +
assumes
 $prepend-trail_{NOT}$:
 $state_{NOT} (prepend-trail L st) = (L \# trail st, clauses_{NOT} st)$ **and**
 $tl-trail_{NOT}$:
 $state_{NOT} (tl-trail st) = (tl (trail st), clauses_{NOT} st)$ **and**
 $add-cls_{NOT}$:
 $state_{NOT} (add-cls_{NOT} C st) = (trail st, \{ \# C \# \} + clauses_{NOT} st)$ **and**
 $remove-cls_{NOT}$:
 $state_{NOT} (remove-cls_{NOT} C st) = (trail st, removeAll-mset C (clauses_{NOT} st))$
begin
lemma
 $trail-prepend-trail[simp]$:
 $trail (prepend-trail L st) = L \# trail st$
and
 $trail-tl-trail_{NOT}[simp]$: $trail (tl-trail st) = tl (trail st)$ **and**
 $trail-add-cls_{NOT}[simp]$: $trail (add-cls_{NOT} C st) = trail st$ **and**

*trail-remove-cls*_{NOT}[simp]: *trail (remove-cls*_{NOT} *C st) = trail st* **and**

clauses-prepend-trail[simp]:

*clauses*_{NOT} (*prepend-trail L st*) = *clauses*_{NOT} *st*

and

clauses-tl-trail[simp]: *clauses*_{NOT} (*tl-trail st*) = *clauses*_{NOT} *st* **and**

*clauses-add-cls*_{NOT}[simp]:

*clauses*_{NOT} (*add-cls*_{NOT} *C st*) = {#*C*#} + *clauses*_{NOT} *st* **and**

*clauses-remove-cls*_{NOT}[simp]:

*clauses*_{NOT} (*remove-cls*_{NOT} *C st*) = *removeAll-mset C (clauses*_{NOT} *st)*

using *prepend-trail*_{NOT}[of *L st*] *tl-trail*_{NOT}[of *st*] *add-cls*_{NOT}[of *C st*] *remove-cls*_{NOT}[of *C st*]

by (*cases state*_{NOT} *st*; *auto*)+

We define the following function doing the backtrack in the trail:

function *reduce-trail-to*_{NOT} :: 'a list \Rightarrow 'st \Rightarrow 'st **where**

*reduce-trail-to*_{NOT} *F S* =

(if *length (trail S) = length F \vee trail S = []* then *S* else *reduce-trail-to*_{NOT} *F (tl-trail S)*)

by *fast*+

termination by (*relation measure* ($\lambda(-, S). \text{length}(\text{trail } S)$)) *auto*

declare *reduce-trail-to*_{NOT}.*simps*[simp del]

Then we need several lemmas about the *reduce-trail-to*_{NOT}.

lemma

shows

*reduce-trail-to*_{NOT}-Nil[simp]: *trail S = [] \implies reduce-trail-to*_{NOT} *F S = S* **and**

*reduce-trail-to*_{NOT}-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}-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}-length-le:

assumes *length F > length (trail S)*

shows *trail (reduce-trail-to*_{NOT} *F S) = []*

using *assms by (induction F S rule: reduce-trail-to*_{NOT}.*induct*)

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

lemma *trail-reduce-trail-to*_{NOT}-Nil[simp]:

*trail (reduce-trail-to*_{NOT} [] *S) = []*

by (*induction [] S rule: reduce-trail-to*_{NOT}.*induct*)

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

lemma *clauses-reduce-trail-to*_{NOT}-Nil:

*clauses*_{NOT} (*reduce-trail-to*_{NOT} [] *S*) = *clauses*_{NOT} *S*

by (*induction [] S 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) \geq 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-toNOT F S) = F
  using assms by (auto simp: trail-reduce-trail-toNOT-drop)

```

lemma *reduce-trail-to_{NOT}-clauses[simp]*:

```

  clausesNOT (reduce-trail-toNOT F S) = clausesNOT S
  by (induction F S rule: reduce-trail-toNOT.induct)
  (simp add: less-imp-diff-less reduce-trail-toNOT.simps)

```

lemma *trail-eq-reduce-trail-to_{NOT}-eq*:

```

  trail S = trail T  $\implies$  trail (reduce-trail-toNOT F S) = trail (reduce-trail-toNOT F T)
  apply (induction F S arbitrary: T rule: reduce-trail-toNOT.induct)
  by (metis trail-tl-trailNOT reduce-trail-toNOT-eq-length reduce-trail-toNOT-length-ne
      reduce-trail-toNOT-Nil)

```

lemma *trail-reduce-trail-to_{NOT}-add-cl_{NOT}[simp]*:

```

  no-dup (trail S)  $\implies$ 
  trail (reduce-trail-toNOT F (add-clNOT C S)) = trail (reduce-trail-toNOT F S)
  by (rule trail-eq-reduce-trail-toNOT-eq) simp

```

lemma *reduce-trail-to_{NOT}-trail-tl-trail-decomp[simp]*:

```

  trail S = F' @ Decided K # F  $\implies$ 
  trail (reduce-trail-toNOT F (tl-trail S)) = F
  apply (rule reduce-trail-toNOT-skip-beginning[of - tl (F' @ Decided K # [])])
  by (cases F') (auto simp add:tl-append reduce-trail-toNOT-skip-beginning)

```

lemma *reduce-trail-to_{NOT}-length*:

```

  length M = length M'  $\implies$  reduce-trail-toNOT M S = reduce-trail-toNOT M' S
  apply (induction M S rule: reduce-trail-toNOT.induct)
  by (simp add: reduce-trail-toNOT.simps)

```

abbreviation *trail-weight where*

trail-weight S \equiv map (($\lambda l.$ 1 + length l) o snd) (get-all-ann-decomposition (trail S))

As we are defining abstract states, the Isabelle equality about them is too strong: we want the weaker equivalence stating that two states are equal if they cannot be distinguished, i.e. given the getter *trail* and *clauses_{NOT}* do not distinguish them.

definition *state-eq_{NOT}* :: 'st \Rightarrow 'st \Rightarrow bool (**infix** \sim 50) **where**

$S \sim T \longleftrightarrow \text{trail } S = \text{trail } T \wedge \text{clauses}_{\text{NOT}} S = \text{clauses}_{\text{NOT}} T$

lemma *state-eq_{NOT}-ref[simp]*:

```

  S  $\sim$  S
  unfolding state-eqNOT-def by auto

```

lemma *state-eq_{NOT}-sym*:

$S \sim T \longleftrightarrow T \sim S$

unfolding *state-eq_{NOT}-def* **by** *auto*

lemma *state-eq_{NOT}-trans*:

$S \sim T \implies T \sim U \implies S \sim U$

unfolding *state-eq_{NOT}-def* **by** *auto*

lemma

shows

state-eq_{NOT}-trail: $S \sim T \implies \text{trail } S = \text{trail } T$ **and**

state-eq_{NOT}-clauses: $S \sim T \implies \text{clauses}_{\text{NOT}} S = \text{clauses}_{\text{NOT}} T$

unfolding *state-eq_{NOT}-def* **by** *auto*

lemmas *state-simp_{NOT}[simp]* = *state-eq_{NOT}-trail* *state-eq_{NOT}-clauses*

lemma *reduce-trail-to_{NOT}-state-eq_{NOT}-compatible*:

assumes *ST*: $S \sim T$

shows *reduce-trail-to_{NOT}* *F* $S \sim \text{reduce-trail-to}_{\text{NOT}} F T$

proof –

have *clauses_{NOT}* (*reduce-trail-to_{NOT}* *F* *S*) = *clauses_{NOT}* (*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

end

Definition of the operation

Each possible is in its own locale.

locale *propagate-ops* =

dpll-state *trail* *clauses_{NOT}* *prepend-trail* *tl-trail* *add-cl_s_{NOT}* *remove-cl_s_{NOT}*

for

trail :: '*st* \Rightarrow ('*v*, *unit*) *ann-lits* **and**

clauses_{NOT} :: '*st* \Rightarrow '*v* *clauses* **and**

prepend-trail :: ('*v*, *unit*) *ann-lit* \Rightarrow '*st* \Rightarrow '*st* **and**

tl-trail :: '*st* \Rightarrow '*st* **and**

add-cl_s_{NOT} :: '*v* *clause* \Rightarrow '*st* \Rightarrow '*st* **and**

remove-cl_s_{NOT} :: '*v* *clause* \Rightarrow '*st* \Rightarrow '*st* +

fixes

propagate-cond :: ('*v*, *unit*) *ann-lit* \Rightarrow '*st* \Rightarrow *bool*

begin

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

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

$\implies \text{undefined-lit } (\text{trail } S) L$

$\implies \text{propagate-cond } (\text{Propagated } L ()) S$

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

$\implies \text{propagate}_{\text{NOT}} S T$

inductive-cases *propagate_{NOT}E*[*elim*]: *propagate_{NOT}* *S* *T*

end

locale *decide-ops* =

dpll-state *trail* *clauses_{NOT}* *prepend-trail* *tl-trail* *add-cl_s_{NOT}* *remove-cl_s_{NOT}*

for

```

trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
clausesNOT :: 'st  $\Rightarrow$  'v clauses and
prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
tl-trail :: 'st  $\Rightarrow$  'st and
add-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
remove-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st
begin
inductive decideNOT :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
decideNOT[intro]: undefined-lit (trail S) L  $\Rightarrow$  atm-of L  $\in$  atms-of-mm (clausesNOT S)
 $\Rightarrow$  T  $\sim$  prepend-trail (Decided L) S
 $\Rightarrow$  decideNOT S T

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

locale backjumping-ops =
dpll-state trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT
for
trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
clausesNOT :: 'st  $\Rightarrow$  'v clauses and
prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
tl-trail :: 'st  $\Rightarrow$  'st and
add-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
remove-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st +
fixes
backjump-conds :: 'v clause  $\Rightarrow$  'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool
begin

inductive backjump where
trail S = F' @ Decided K# F
 $\Rightarrow$  T  $\sim$  prepend-trail (Propagated L ()) (reduce-trail-toNOT F S)
 $\Rightarrow$  C  $\in$  # clausesNOT S
 $\Rightarrow$  trail S  $\models_{as}$  CNot C
 $\Rightarrow$  undefined-lit F L
 $\Rightarrow$  atm-of L  $\in$  atms-of-mm (clausesNOT S)  $\cup$  atm-of ' (lits-of-l (trail S))
 $\Rightarrow$  clausesNOT S  $\models_{pm}$  C' + {#L#}
 $\Rightarrow$  F  $\models_{as}$  CNot C'
 $\Rightarrow$  backjump-conds C C' L S T
 $\Rightarrow$  backjump S T

inductive-cases backjumpE: backjump S T

```

The condition $\text{atm-of } L \in \text{atms-of-mm } (\text{clauses}_{\text{NOT}} S) \cup \text{atm-of ' } (\text{lits-of-l } (\text{trail } S))$ is not implied by the condition $\text{clauses}_{\text{NOT}} S \models_{pm} C' + \{\#L\}$ (no negation).

end

5.2.3 DPLL with backjumping

```

locale dpll-with-backjumping-ops =
propagate-ops trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT propagate-conds +
decide-ops trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT +
backjumping-ops trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT backjump-conds
for
trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
clausesNOT :: 'st  $\Rightarrow$  'v clauses and
prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
tl-trail :: 'st  $\Rightarrow$  'st and

```


$add-cls_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st \text{ and}$
 $remove-cls_{NOT} :: 'v \text{ clause} \Rightarrow 'st \Rightarrow 'st \text{ and}$
 $inv :: 'st \Rightarrow bool \text{ and}$
 $backjump-conds :: 'v \text{ clause} \Rightarrow 'v \text{ clause} \Rightarrow 'v \text{ literal} \Rightarrow 'st \Rightarrow 'st \Rightarrow bool \text{ and}$
 $propagate-conds :: ('v, unit) \text{ ann-lit} \Rightarrow 'st \Rightarrow bool +$
assumes
 $bj\text{-can-jump:}$
 $\bigwedge S \ C \ F' \ K \ F \ L.$
 $inv \ S \Longrightarrow$
 $no\text{-dup} \ (trail \ S) \Longrightarrow$
 $trail \ S = F' @ Decided \ K \ \# \ F \Longrightarrow$
 $C \in \# \ clauses_{NOT} \ S \Longrightarrow$
 $trail \ S \models_{as} CNot \ C \Longrightarrow$
 $undefined\text{-lit} \ F \ L \Longrightarrow$
 $atm\text{-of} \ L \in atm\text{-of}\text{-mm} \ (clauses_{NOT} \ S) \cup atm\text{-of} \ ' \ (lits\text{-of}\text{-l} \ (F' @ Decided \ K \ \# \ F)) \Longrightarrow$
 $clauses_{NOT} \ S \models_{pm} C' + \{\#L\# \} \Longrightarrow$
 $F \models_{as} CNot \ C' \Longrightarrow$
 $\neg no\text{-step} \ backjump \ S$
begin

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

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

Definition

We define $dp\text{ll}$ with backjumping:

inductive $dp\text{ll}\text{-bj} :: 'st \Rightarrow 'st \Rightarrow bool$ **for** $S :: 'st$ **where**
 $bj\text{-decide}_{NOT}: decide_{NOT} \ S \ S' \Longrightarrow dp\text{ll}\text{-bj} \ S \ S' \mid$
 $bj\text{-propagate}_{NOT}: propagate_{NOT} \ S \ S' \Longrightarrow dp\text{ll}\text{-bj} \ S \ S' \mid$
 $bj\text{-backjump}: backjump \ S \ S' \Longrightarrow dp\text{ll}\text{-bj} \ S \ S'$

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

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

lemma $dp\text{ll}\text{-bj}\text{-all-induct}[\text{consumes } 2, \text{ case-names } decide_{NOT} \ propagate_{NOT} \ backjump]:$

fixes $S \ T :: 'st$

assumes

$dp\text{ll}\text{-bj} \ S \ T$ **and**

$inv \ S$

$\bigwedge L \ T. \text{undefined-lit} \ (trail \ S) \ L \Longrightarrow atm\text{-of} \ L \in atm\text{-of}\text{-mm} \ (clauses_{NOT} \ S)$

$\Longrightarrow T \sim \text{prepend-trail} \ (Decided \ L) \ S$

$\Longrightarrow P \ S \ T$ **and**

$\bigwedge C \ L \ T. C + \{\#L\# \} \in \# \ clauses_{NOT} \ S \Longrightarrow trail \ S \models_{as} CNot \ C \Longrightarrow \text{undefined-lit} \ (trail \ S) \ L$

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

$\Longrightarrow P \ S \ T$ **and**

$\bigwedge C \ F' \ K \ F \ L \ C' \ T. C \in \# \ clauses_{NOT} \ S \Longrightarrow F' @ Decided \ K \ \# \ F \models_{as} CNot \ C$

$\Longrightarrow trail \ S = F' @ Decided \ K \ \# \ F$

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

$\Longrightarrow atm\text{-of} \ L \in atm\text{-of}\text{-mm} \ (clauses_{NOT} \ S) \cup atm\text{-of} \ ' \ (lits\text{-of}\text{-l} \ (F' @ Decided \ K \ \# \ F))$

$\Longrightarrow clauses_{NOT} \ S \models_{pm} C' + \{\#L\# \}$

$\Longrightarrow F \models_{as} CNot \ C'$

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

$\Longrightarrow P \ S \ T$

shows $P \ S \ T$
apply (*induct* T *rule*: *dpll-bj-induct*[*OF local.dpll-with-backjumping-ops-axioms*])
 apply (*rule* *assms*(1))
 using *assms*(3) **apply** *blast*
 apply (*elim propagate*_{NOT}*E*) **using** *assms*(4) **apply** *blast*
apply (*elim backjumpE*) **using** *assms*(5) $\langle \text{inv } S \rangle$ **by** *simp*

Basic properties

First, some better suited induction principle **lemma** *dpll-bj-clauses*:

assumes *dpll-bj* $S \ T$ **and** *inv* S
shows *clauses*_{NOT} $S = \text{clauses}_{NOT} \ T$
using *assms* **by** (*induction rule*: *dpll-bj-all-induct*) *auto*

No duplicates in the trail **lemma** *dpll-bj-no-dup*:

assumes *dpll-bj* $S \ T$ **and** *inv* S
and *no-dup* (*trail* S)
shows *no-dup* (*trail* T)
using *assms* **by** (*induction rule*: *dpll-bj-all-induct*)
(auto simp add: defined-lit-map reduce-trail-to_{NOT}-skip-beginning)

Valuations **lemma** *dpll-bj-sat-iff*:

assumes *dpll-bj* $S \ T$ **and** *inv* S
shows $I \models^{sm} \text{clauses}_{NOT} \ S \longleftrightarrow I \models^{sm} \text{clauses}_{NOT} \ T$
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-mm* (*clauses*_{NOT} S) = *atms-of-mm* (*clauses*_{NOT} T)
using *assms* **by** (*induction rule*: *dpll-bj-all-induct*) *auto*

lemma *dpll-bj-atms-in-trail*:

assumes
 dpll-bj $S \ T$ **and**
 inv S **and**
 $\text{atm-of } ' (\text{lits-of-l } (\text{trail } S)) \subseteq \text{atms-of-mm } (\text{clauses}_{NOT} \ S)$
shows $\text{atm-of } ' (\text{lits-of-l } (\text{trail } T)) \subseteq \text{atms-of-mm } (\text{clauses}_{NOT} \ S)$
using *assms* **by** (*induction rule*: *dpll-bj-all-induct*)
(auto simp: in-plus-implies-atm-of-on-atms-of-ms reduce-trail-to_{NOT}-skip-beginning)

lemma *dpll-bj-atms-in-trail-in-set*:

assumes *dpll-bj* $S \ T$ **and**
 inv S **and**
 $\text{atms-of-mm } (\text{clauses}_{NOT} \ S) \subseteq A$ **and**
 $\text{atm-of } ' (\text{lits-of-l } (\text{trail } S)) \subseteq A$
shows $\text{atm-of } ' (\text{lits-of-l } (\text{trail } T)) \subseteq A$
using *assms* **by** (*induction rule*: *dpll-bj-all-induct*)
(auto simp: in-plus-implies-atm-of-on-atms-of-ms)

lemma *dpll-bj-all-decomposition-implies-inv*:

assumes
 dpll-bj $S \ T$ **and**
 inv: *inv* S **and**

decomp: *all-decomposition-implies-m* (*clauses*_{NOT} *S*) (*get-all-ann-decomposition* (*trail S*))
shows *all-decomposition-implies-m* (*clauses*_{NOT} *T*) (*get-all-ann-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*_{NOT} *S*
obtain *a y l* **where** *ay*: *get-all-ann-decomposition* ?*M'* = (*a, y*) # *l*
by (*cases* *get-all-ann-decomposition* ?*M'*) *fastforce* +
then have *M'*: ?*M'* = *y* @ *a* **using** *get-all-ann-decomposition-decomp*[*of* ?*M'*] **by** *auto*
have *M*: *get-all-ann-decomposition* (*trail S*) = (*a, tl y*) # *l*
using *ay undef* **by** (*cases* *get-all-ann-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-ann-decomposition-decomp* **by** *force*
have *a-Un-N-M*: *unmark-l a* ∪ *set-mset* ?*N* ⊨_{ps} *unmark-l* (*tl y*)
using *decomp ay unfolding all-decomposition-implies-def* **by** (*simp add*: *M*) +

moreover have *unmark-l a* ∪ *set-mset* ?*N* ⊨_p {#*L*#} (**is** ?*I* ⊨_p -)
proof (*rule true-clss-clss-plus-CNot*)
show ?*I* ⊨_p *C* + {#*L*#}
using *propa propagate*_{NOT}.*prems* **by** (*auto dest*!: *true-clss-clss-in-imp-true-clss-clss*)
next
have *unmark-l* ?*M'* ⊨_{ps} *CNot C*
using (*trail S* ⊨_{as} *CNot C*) *undef* **by** (*auto simp add*: *true-annots-true-clss-clss*)
have *a1*: *unmark-l a* ∪ *unmark-l* (*tl y*) ⊨_{ps} *CNot C*
using *propagate*_{NOT}.*hyps*(2) *tr-S true-annots-true-clss-clss*
by (*force simp add*: *image-Un sup-commute*)
then have *unmark-l a* ∪ *set-mset* (*clauses*_{NOT} *S*) ⊨_{ps} *unmark-l a* ∪ *unmark-l* (*tl y*)
using *a-Un-N-M true-clss-clss-def* **by** *blast*
then show *unmark-l a* ∪ *set-mset* (*clauses*_{NOT} *S*) ⊨_{ps} *CNot C*
using *a1* **by** (*meson true-clss-clss-left-right true-clss-clss-union-and*
true-clss-clss-union-l-r)
qed
ultimately have *unmark-l a* ∪ *set-mset* ?*N* ⊨_{ps} *unmark-l* ?*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*_{NOT} *S*) (*get-all-ann-decomposition* *F*)
using *decomp unfolding tr all-decomposition-implies-def*
by (*metis* (*no-types, lifting*) *get-all-ann-decomposition.simps*(1)
get-all-ann-decomposition-never-empty hd-Cons-tl insert-iff list.sel(3) *list.set*(2)
tl-get-all-ann-decomposition-skip-some)

obtain *a b li* **where** *F*: *get-all-ann-decomposition* *F* = (*a, b*) # *li*
by (*cases* *get-all-ann-decomposition F*) *auto*
have *F* = *b* @ *a*

```

  using get-all-ann-decomposition-decomp[of F a b] F by auto
have a-N-b:unmark-l a  $\cup$  set-mset (clausesNOT S)  $\models_{ps}$  unmark-l b
  using decomp unfolding all-decomposition-implies-def by (auto simp add: F)

have F-D: unmark-l F  $\models_{ps}$  CNot D
  using  $\langle F \models_{as} CNot D \rangle$  by (simp add: true-annots-true-clss-clss)
then have unmark-l a  $\cup$  unmark-l b  $\models_{ps}$  CNot D
  unfolding  $\langle F = b @ a \rangle$  by (simp add: image-Un sup commute)
have a-N-CNot-D: unmark-l a  $\cup$  set-mset (clausesNOT S)  $\models_{ps}$  CNot D  $\cup$  unmark-l 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-l a  $\cup$  set-mset (clausesNOT S)  $\models_p$  D+{#L#}
  by (simp add: N-C)
have unmark-l a  $\cup$  set-mset (clausesNOT 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

```

Termination

Using a proper measure lemma length-get-all-ann-decomposition-append-Decided:

```

length (get-all-ann-decomposition (F' @ Decided K # F)) =
  length (get-all-ann-decomposition F')
  + length (get-all-ann-decomposition (Decided K # F))
  - 1

```

by (induction F' rule: ann-lit-list-induct) auto

lemma take-length-get-all-ann-decomposition-decided-sandwich:

```

take (length (get-all-ann-decomposition F))
  (map (f o snd) (rev (get-all-ann-decomposition (F' @ Decided K # F))))
=
  map (f o snd) (rev (get-all-ann-decomposition F))

```

proof (induction F' rule: ann-lit-list-induct)

```

  case Nil
  then show ?case by auto

```

next

```

  case (Decided K)
  then show ?case by (simp add: length-get-all-ann-decomposition-append-Decided)

```

next

```

  case (Propagated L m F') note IH = this(1)
  obtain a b l where F': get-all-ann-decomposition (F' @ Decided K # F) = (a, b) # l
    by (cases get-all-ann-decomposition (F' @ Decided K # F)) auto
  have length (get-all-ann-decomposition F) - length l = 0
    using length-get-all-ann-decomposition-append-Decided[of F' K F]
    unfolding F' by (cases get-all-ann-decomposition F') auto
  then show ?case
    using IH by (simp add: F')

```

qed

lemma length-get-all-ann-decomposition-length:

```

length (get-all-ann-decomposition M)  $\leq$  1 + length M
by (induction M rule: ann-lit-list-induct) auto

```

lemma *length-in-get-all-ann-decomposition-bounded*:
assumes $i: i \in \text{set } (\text{trail-weight } S)$
shows $i \leq \text{Suc } (\text{length } (\text{trail } S))$
proof –
obtain $a \ b$ **where**
 $(a, b) \in \text{set } (\text{get-all-ann-decomposition } (\text{trail } S))$ **and**
 $ib: i = \text{Suc } (\text{length } b)$
using i **by** *auto*
then obtain c **where** $\text{trail } S = c @ b @ a$
using *get-all-ann-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-ann-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* :: $'b \text{ literal multiset set} \Rightarrow 'a \text{ list} \Rightarrow \text{nat}$ **where**
 $\text{unassigned-lit } N \ M \equiv \text{card } (\text{atms-of-ms } N) - \text{length } M$

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

fixes $M :: ('v, \text{unit}) \text{ ann-lits}$ **and** $N :: 'v \text{ clauses}$

assumes

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

$\text{inv } S$ **and**

$NA: \text{atms-of-mm } (\text{clauses}_{NOT} \ S) \subseteq \text{atms-of-ms } A$ **and**

$MA: \text{atm-of } ' \text{ lits-of-l } (\text{trail } S) \subseteq \text{atms-of-ms } A$ **and**

$n\text{-d}: \text{no-dup } (\text{trail } S)$ **and**

$\text{finite}: \text{finite } A$

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 ($\text{propagate}_{NOT} \ C \ L$) **note** $CLN = \text{this}(1)$ **and** $MC = \text{this}(2)$ **and** $\text{undef-L} = \text{this}(3)$ **and** $T = \text{this}(4)$

have $\text{incl}: \text{atm-of } ' \text{ lits-of-l } (\text{Propagated } L \ ()) \# \text{trail } S \subseteq \text{atms-of-ms } A$

using $\text{propagate}_{NOT} \ \text{dpll-bj-atms-in-trail-in-set} \ \text{bj-propagate}_{NOT} \ NA \ MA \ CLN$

by (*auto simp: in-plus-implies-atm-of-on-atms-of-ms*)

have $\text{no-dup}: \text{no-dup } (\text{Propagated } L \ ()) \# \text{trail } S$

using $\text{defined-lit-map } n\text{-d } \text{undef-L}$ **by** *auto*

obtain $a \ b \ l$ **where** $M: \text{get-all-ann-decomposition } (\text{trail } S) = (a, b) \# l$

by (*cases get-all-ann-decomposition (trail S) auto*)

have $b\text{-le-M}: \text{length } b \leq \text{length } (\text{trail } S)$

using $\text{get-all-ann-decomposition-decomp[of trail S]}$ **by** (*simp add: M*)

have $\text{finite } (\text{atms-of-ms } A)$ **using** finite **by** *simp*

then have $\text{length } (\text{Propagated } L \ ()) \# \text{trail } S \leq \text{card } (\text{atms-of-ms } A)$

using $\text{incl } \text{finite}$ **unfolding** $\text{no-dup-length-eq-card-atm-of-lits-of-l[OF no-dup]}$

```

    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-l (Decided L # (trail S))  $\subseteq$  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 (Decided L # (trail S))
  using defined-lit-map n-d undef-L by auto
obtain a b l where M: get-all-ann-decomposition (trail S) = (a, b) # l
  by (cases get-all-ann-decomposition (trail S)) auto

then have length (Decided L # (trail S))  $\leq$  card (atms-of-ms A)
  using incl finite unfolding no-dup-length-eq-card-atm-of-lits-of-l[OF no-dup]
  by (simp add: card-mono)
show ?case using T undef-L by (simp add:  $\mu_C$ -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-l (Propagated L () # F)  $\subseteq$  atms-of-ms A
  using dpll-bj-atms-in-trail-in-set NA MA L by (auto simp: tr-S)

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-ann-decomposition (trail S) = (a, b) # l
  by (cases get-all-ann-decomposition (trail S)) auto
have b-le-M: length b  $\leq$  length (trail S)
  using get-all-ann-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)  $\leq$  card (atms-of-ms A)
  using incl finite unfolding no-dup-length-eq-card-atm-of-lits-of-l[OF no-dup]
  by (simp add: card-mono)
have tr-S-le-A: length (trail S)  $\leq$  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-l)
obtain a b l where F: get-all-ann-decomposition F = (a, b) # l
  by (cases get-all-ann-decomposition F) auto
then have F = b @ a
  using get-all-ann-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 ( $\lambda a$ . Suc (length (snd a))) (rev (get-all-ann-decomposition (F' @ Decided K # F)))
  = map ( $\lambda a$ . Suc (length (snd a))) (rev (get-all-ann-decomposition F)) @ rem
  using take-length-get-all-ann-decomposition-decided-sandwich[of F  $\lambda a$ . Suc (length a) F' K]
  unfolding o-def by (metis append-take-drop-id)
then have rem: map ( $\lambda a$ . Suc (length (snd a)))
  (get-all-ann-decomposition (F' @ Decided K # F))
  = rev rem @ map ( $\lambda a$ . Suc (length (snd a))) ((get-all-ann-decomposition F))
  by (simp add: rev-map[symmetric] rev-swap)

```

```

have length (rev rem @ map (λa. Suc (length (snd a))) (get-all-ann-decomposition F))
  ≤ Suc (card (atms-of-ms A))
using arg-cong[OF rem, of length] tr-S-le-A
length-get-all-ann-decomposition-length[of F' @ Decided 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-ann-decomposition-bounded[of - S] unfolding tr-S
  by (force simp add: o-def rem dest!: H intro: length-get-all-ann-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-mm (clauses_{NOT} S) ⊆ atms-of-ms A* **and**
M-A: *atm-of ' lits-of-l (trail S) ⊆ atms-of-ms A* **and**
nd: *no-dup (trail S)* **and**
fin-A: *finite A*

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

proof –

```

let ?b = 2 + 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-l (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-l 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-l nd')
have l-trail-weight-M: length (trail-weight T) ≤ 1 + card (atms-of-ms A)
  using l-M'-A length-get-all-ann-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-ann-decomposition-bounded[of - T] l-M'-A
  by (metis (no-types, lifting) H Nat.le-trans add-2-eq-Suc' not-le not-less-eq-eq)

```

```

from dpll-bj-trail-mes-increasing-prop[OF dpll 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 μ_C -bounded[OF bounded-M l-trail-weight-M]
have $\mu_C \text{ ?s ?b (trail-weight } T) \leq \text{?b} \wedge \text{?s}$ **by** *auto*
ultimately show *?thesis* **by** *linarith*
qed

lemma *wf-dpll-bj*:
assumes *fin*: *finite A*
shows *wf* $\{(T, S). \text{dpll-bj } S \text{ } T$
 $\wedge \text{atms-of-mm (clauses}_{NOT} S) \subseteq \text{atms-of-ms } A \wedge \text{atm-of ' lits-of-l (trail } S) \subseteq \text{atms-of-ms } A$
 $\wedge \text{no-dup (trail } S) \wedge \text{inv } S\}$
(is *wf* *?A*)
proof (*rule wf-bounded-measure*[of -
 $\lambda \cdot. (2 + \text{card (atms-of-ms } A)) \wedge (1 + \text{card (atms-of-ms } A))$
 $\lambda S. \mu_C (1 + \text{card (atms-of-ms } A)) (2 + \text{card (atms-of-ms } A)) (\text{trail-weight } S)]$)
fix *a b* :: '*st*
let *?b* = $2 + \text{card (atms-of-ms } A)$
let *?s* = $1 + \text{card (atms-of-ms } A)$
let *?μ* = $\mu_C \text{ ?s ?b}$
assume *ab*: $(b, a) \in \text{?A}$

have *fin-A*: *finite (atms-of-ms A)*
using *fin* **by** *auto*
have
dpll-bj: *dpll-bj a b and*
N-A: *atms-of-mm (clauses*_{NOT} *a) ⊆ atms-of-ms A and*
M-A: *atm-of ' lits-of-l (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-l (trail b) ⊆ atms-of-ms A*
by (*meson M-A N-A <dpll-bj a b> dpll-bj-atms-in-trail-in-set inv*)
have *nd'*: *no-dup (trail b)*
using *<dpll-bj a b> dpll-bj-no-dup nd inv* **by** *blast*
{ fix *i* :: *nat* **and** *xs* :: '*a list*
have $i < \text{length } xs \implies \text{length } xs - \text{Suc } i < \text{length } xs$
by *auto*
then have *H*: $i < \text{length } xs \implies xs ! i \in \text{set } xs$
using *rev-nth*[of *i xs*] **unfolding** *in-set-conv-nth* **by** (*force simp add: in-set-conv-nth*)
} note *H = this*

have *l-M-A*: $\text{length (trail } a) \leq \text{card (atms-of-ms } A)$
by (*simp add: fin-A M-A card-mono no-dup-length-eq-card-atm-of-lits-of-l nd*)
have *l-M'-A*: $\text{length (trail } b) \leq \text{card (atms-of-ms } A)$
by (*simp add: fin-A M'-A card-mono no-dup-length-eq-card-atm-of-lits-of-l nd'*)
have *l-trail-weight-M*: $\text{length (trail-weight } b) \leq 1 + \text{card (atms-of-ms } A)$
using *l-M'-A length-get-all-ann-decomposition-length*[of *trail b*] **by** *auto*
have *bounded-M*: $\forall i < \text{length (trail-weight } b). (\text{trail-weight } b) ! i < \text{card (atms-of-ms } A) + 2$
using *length-in-get-all-ann-decomposition-bounded*[of - *b*] *l-M'-A*
by (*metis (no-types, lifting) Nat.le-trans One-nat-def Suc-1 add.right-neutral add-Suc-right*
le-imp-less-Suc less-eq-Suc-le nth-mem)

from *dpll-bj-trail-mes-increasing-prop*[OF *dpll-bj inv N-A M-A nd fin*]
have $\mu_C \text{ ?s ?b (trail-weight } a) < \mu_C \text{ ?s ?b (trail-weight } b)$ **by** *simp*
moreover from μ_C -bounded[OF bounded-M l-trail-weight-M]
have $\mu_C \text{ ?s ?b (trail-weight } b) \leq \text{?b} \wedge \text{?s}$ **by** *auto*

ultimately show $?b \wedge ?s \leq ?b \wedge ?s \wedge$
 $\mu_C ?s ?b \text{ (trail-weight } b) \leq ?b \wedge ?s \wedge$
 $\mu_C ?s ?b \text{ (trail-weight } a) < \mu_C ?s ?b \text{ (trail-weight } b)$
 by *blast*
 qed

Normal Forms

We prove that given a normal form of DPLL, with some structural invariants, then 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* rule tells us that every variable in N has a value.
2. The assumption $\neg M \models_{as} N$ implies that there is conflict.
3. There is at least one decision in the trail (otherwise, M would be a model of the set of clauses 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 $A :: 'v \text{ clause set}$ **and** $S \ T :: 'st$

assumes

atms-of-mm (*clauses*_{NOT} S) \subseteq *atms-of-ms* A **and**

atm-of ' *lits-of-l* (*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*_{NOT} S) (*get-all-ann-decomposition* (*trail* S))

shows *unsatisfiable* (*set-mset* (*clauses*_{NOT} S))

\vee (*trail* $S \models_{asm}$ *clauses*_{NOT} $S \wedge$ *satisfiable* (*set-mset* (*clauses*_{NOT} S)))

proof –

let $?N = \text{set-mset} (\text{clauses}_{NOT} S)$

let $?M = \text{trail } S$

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** $\text{sat} = \text{this}(1)$ **and** $M = \text{this}(2)$

obtain C **where** $C \in ?N$ **and** $\neg ?M \models_a C$ **using** M **unfolding** *true-annots-def* **by** *auto*

obtain $I :: 'v \text{ literal set}$ **where**

$I \models_s ?N$ **and**

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

tot: *total-over-m* $I ?N$ **and**

atm-I-N: *atm-of* ' $I \subseteq \text{atms-of-ms } ?N$

```

using sat unfolding satisfiable-def-min by auto
let  $?I = I \cup \{P \mid P. P \in \text{ lits-of-}l \text{ } ?M \wedge \text{ atm-of } P \notin \text{ atm-of ' } I\}$ 
let  $?O = \{\text{unmark } L \mid L. \text{ is-decided } L \wedge L \in \text{ set } ?M \wedge \text{ atm-of } (\text{lit-of } L) \notin \text{ atms-of-ms } ?N\}$ 
have  $\text{cons-}I'$ : 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  $\text{tot-}I'$ : total-over-m  $?I$   $(?N \cup \text{unmark-}l \text{ } ?M)$ 
  using tot atm-I-N unfolding total-over-m-def total-over-set-def
  by (fastforce simp: image-iff lits-of-def)
have  $\{P \mid P. P \in \text{ lits-of-}l \text{ } ?M \wedge \text{ atm-of } P \notin \text{ atm-of ' } I\} \models_s ?O$ 
  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  $\text{tot}'$ : total-over-m  $?I$   $(?N \cup ?O)$ 
  using atm-I-N tot unfolding total-over-m-def total-over-set-def
  by (force simp: lits-of-def elim!: is-decided-ex-Decided)

have  $\text{atms-}N\text{-}M$ :  $\text{atms-of-ms } ?N \subseteq \text{ atm-of ' } \text{ lits-of-}l \text{ } ?M$ 
proof (rule ccontr)
  assume  $\neg ?thesis$ 
  then obtain  $l :: 'v$  where
     $l\text{-}N$ :  $l \in \text{ atms-of-ms } ?N$  and
     $l\text{-}M$ :  $l \notin \text{ atm-of ' } \text{ lits-of-}l \text{ } ?M$ 
  by auto
  have undefined-lit  $?M$   $(\text{Pos } l)$ 
    using  $l\text{-}M$  by (metis Decided-Propagated-in-iff-in-lits-of-l
      atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set literal.sel(1))
  from  $\text{bj-decide}_{NOT}[\text{OF decide}_{NOT}[\text{OF this}]]$  show False
    using  $l\text{-}N$   $n\text{-}s$  by (metis literal.sel(1) state-eq_{NOT}-ref)
qed
have  $?M \models_{as} C\text{Not } C$ 
  apply (rule all-variables-defined-not-imply-cnot)
  using  $\langle C \in \text{ set-mset } (\text{clauses}_{NOT} S) \rangle \langle \neg \text{ trail } S \models_a C \rangle$ 
   $\text{atms-}N\text{-}M$  by (auto dest: atms-of-atms-of-ms-mono)
have  $\exists l \in \text{ set } ?M. \text{ is-decided } l$ 
proof (rule ccontr)
  let  $?O = \{\text{unmark } L \mid L. \text{ is-decided } L \wedge L \in \text{ set } ?M \wedge \text{ atm-of } (\text{lit-of } L) \notin \text{ atms-of-ms } ?N\}$ 
  have  $\vartheta[\text{iff}]: \bigwedge I. \text{ total-over-m } I \text{ } (?N \cup ?O \cup \text{unmark-}l \text{ } ?M)$ 
     $\longleftrightarrow \text{ total-over-m } I \text{ } (?N \cup \text{unmark-}l \text{ } ?M)$ 
  unfolding total-over-set-def total-over-m-def atms-of-ms-def by blast
  assume  $\neg ?thesis$ 
  then have  $[\text{simp}]: \{\text{unmark } L \mid L. \text{ is-decided } L \wedge L \in \text{ set } ?M\}$ 
     $= \{\text{unmark } L \mid L. \text{ is-decided } L \wedge L \in \text{ set } ?M \wedge \text{ atm-of } (\text{lit-of } L) \notin \text{ atms-of-ms } ?N\}$ 
  by auto
  then have  $?N \cup ?O \models_{ps} \text{unmark-}l \text{ } ?M$ 
    using all-decomposition-implies-propagated-lits-are-implied  $[\text{OF decomp}]$  by auto

  then have  $?I \models_s \text{unmark-}l \text{ } ?M$ 
    using  $\text{cons-}I' \text{ } I'\text{-}N \text{ tot-}I' \langle I \models_s ?N \cup ?O \rangle$  unfolding  $\vartheta$  true-clss-clss-def by blast
  then have  $\text{ lits-of-}l \text{ } ?M \subseteq ?I$ 
    unfolding true-clss-def lits-of-def by auto
  then have  $?M \models_{as} ?N$ 
    using  $I'\text{-}N \langle C \in ?N \rangle \langle \neg ?M \models_a C \rangle \text{cons-}I' \text{atms-}N\text{-}M$ 
    by (meson  $\langle \text{trail } S \models_{as} C\text{Not } C \rangle$  consistent-CNot-not rev-subsetD sup-ge1 true-annot-def
      true-annots-def true-clss-mono-set-mset-l true-clss-def)

```

```

    then show False using M by fast
qed
from List.split-list-first-propE[OF this] obtain K :: 'v literal and
  F F' :: ('v, unit) ann-lits where
  M-K: ?M = F' @ Decided K # F and
  nm:  $\forall f \in \text{set } F'. \neg \text{is-decided } f$ 
  unfolding is-decided-def by metis
let ?K = Decided K :: ('v, unit) ann-lit
have ?K ∈ set ?M
  unfolding M-K by auto
let ?C = image-mset lit-of {#L ∈ #mset ?M. is-decided L ∧ L ≠ ?K #} :: 'v clause
let ?C' = set-mset (image-mset ( $\lambda L. 'v \text{ literal. } \{ \#L \# \}$ ) (?C + unmark ?K))
have ?N ∪ {unmark L | L. is-decided L ∧ L ∈ set ?M}  $\models_{ps}$  unmark-l ?M
  using all-decomposition-implies-propagated-lits-are-implied[OF decomp] .
moreover have C': ?C' = {unmark L | L. is-decided L ∧ L ∈ set ?M}
  unfolding M-K by standard force+
ultimately have N-C-M: ?N ∪ ?C'  $\models_{ps}$  unmark-l ?M
  by auto
have N-M-False: ?N ∪ ( $\lambda L. \text{unmark } L$ ) ' (set ?M)  $\models_{ps}$  {{#}}
  using M < ?M  $\models_{as}$  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'  $\models_{ps}$  {{#}}
  proof -
    have A: ?N ∪ ?C' ∪ unmark-l ?M = ?N ∪ unmark-l ?M
      unfolding M-K by auto
    show ?thesis
      using true-clss-clss-left-right[OF N-C-M, of {{#}}] N-M-False unfolding A by auto
  qed
have ?N  $\models_p$  image-mset uminus ?C + {#-K #}
  unfolding true-clss-clss-def true-clss-clss-def total-over-m-def
proof (intro allI impI)
  fix I
  assume
    tot: total-over-set I (atms-of-ms (?N ∪ {image-mset uminus ?C + {#-K #}})) and
    cons: consistent-interp I and
    I  $\models_s$  ?N
  have (K ∈ I ∧ -K ∉ I) ∨ (-K ∈ I ∧ K ∉ I)
    using cons tot unfolding consistent-interp-def by (cases K) auto
  have {a ∈ set (trail S). is-decided a ∧ a ≠ Decided K} =
    set (trail S) ∩ {L. is-decided L ∧ L ≠ Decided K}
  by auto
  then have tot': total-over-set I
    (atm-of ' lit-of ' (set ?M ∩ {L. is-decided L ∧ L ≠ Decided K}))
    using tot by (auto simp add: atms-of-uminus-lit-atm-of-lit-of)
  { fix x :: ('v, unit) ann-lit
    assume
      a3: lit-of x ∉ I and
      a1: x ∈ set ?M and
      a4: is-decided x and
      a5: x ≠ Decided K
    then have Pos (atm-of (lit-of x)) ∈ I ∨ Neg (atm-of (lit-of x)) ∈ 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 ∈ 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  $\langle ?N \cup ?C' \models_{ps} \{\{\#\}\} \rangle \text{ tot cons } \langle I \models_s ?N \rangle$ 
  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  $I \models \text{image-mset uminus } ?C + \{\# - K\# \}$ 
  unfolding true-clss-def true-cl-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  $F \models_{as} CNot (\text{image-mset uminus } ?C)$ 
  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-decided L \wedge L \neq Decided K\#})]
     $\langle C \in ?N \rangle \text{ n-s } \langle ?M \models_{as} CNot C \rangle \text{ bj-backjump inv } \langle \text{no-dup (trail S)} \rangle$  unfolding M-K by auto
  then show ?thesis by fast
qed auto
qed

end — End of dpll-with-backjumping-ops

locale dpll-with-backjumping =
  dpll-with-backjumping-ops trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT inv
  backjump-conds propagate-conds
for
  trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
  clausesNOT :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  remove-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  inv :: 'st  $\Rightarrow$  bool and
  backjump-conds :: 'v clause  $\Rightarrow$  'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool and
  propagate-conds :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  bool
  +
  assumes dpll-bj-inv:  $\bigwedge S T. \text{dpll-bj } S T \Longrightarrow \text{inv } S \Longrightarrow \text{inv } T$ 
begin

lemma rtrancpl-dpll-bj-inv:
  assumes dpll-bj** S T 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 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 *rtranclp-dpll-bj-atms-of-ms-clauses-inv*:

assumes

*dpll-bj** S T and inv S*

shows *atms-of-mm (clauses_{NOT} S) = atms-of-mm (clauses_{NOT} T)*

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

(auto dest: rtranclp-dpll-bj-inv dpll-bj-atms-of-ms-clauses-inv)

lemma *rtranclp-dpll-bj-atms-in-trail*:

assumes

*dpll-bj** S T and*

inv S and

atm-of ' (lits-of-l (trail S)) ⊆ atms-of-mm (clauses_{NOT} S)

shows *atm-of ' (lits-of-l (trail T)) ⊆ atms-of-mm (clauses_{NOT} T)*

using *assms apply (induction rule: rtranclp-induct)*

using *dpll-bj-atms-in-trail dpll-bj-atms-of-ms-clauses-inv rtranclp-dpll-bj-inv by auto*

lemma *rtranclp-dpll-bj-sat-iff*:

assumes *dpll-bj** S T and inv S*

shows *I ⊨_{sm} clauses_{NOT} S ⟷ I ⊨_{sm} clauses_{NOT} T*

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

(auto dest!: dpll-bj-sat-iff simp: rtranclp-dpll-bj-inv)

lemma *rtranclp-dpll-bj-atms-in-trail-in-set*:

assumes

*dpll-bj** S T and*

inv S

atms-of-mm (clauses_{NOT} S) ⊆ A and

atm-of ' (lits-of-l (trail S)) ⊆ A

shows *atm-of ' (lits-of-l (trail T)) ⊆ A*

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

(auto dest: rtranclp-dpll-bj-inv

simp: dpll-bj-atms-in-trail-in-set rtranclp-dpll-bj-atms-of-ms-clauses-inv rtranclp-dpll-bj-inv)

lemma *rtranclp-dpll-bj-all-decomposition-implies-inv*:

assumes

*dpll-bj** S T and*

inv S

all-decomposition-implies-m (clauses_{NOT} S) (get-all-ann-decomposition (trail S))

shows *all-decomposition-implies-m (clauses_{NOT} T) (get-all-ann-decomposition (trail T))*

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

(auto intro: dpll-bj-all-decomposition-implies-inv simp: rtranclp-dpll-bj-inv)

lemma *rtranclp-dpll-bj-inv-incl-dpll-bj-inv-trancl*:

{(T, S). dpll-bj⁺⁺ S T

∧ atms-of-mm (clauses_{NOT} S) ⊆ atms-of-ms A ∧ atm-of ' lits-of-l (trail S) ⊆ atms-of-ms A

∧ no-dup (trail S) ∧ inv S}

⊆ {(T, S). dpll-bj S T ∧ atms-of-mm (clauses_{NOT} S) ⊆ atms-of-ms A

∧ atm-of ' lits-of-l (trail S) ⊆ atms-of-ms A ∧ no-dup (trail S) ∧ inv S}

}⁺ (is ?A ⊆ ?B⁺)

proof *standard*

fix *x*

assume *x-A: x ∈ ?A*

obtain *S T::'st where*

x[simp]: x = (T, S) by (cases x) auto

have

$dpll\text{-}bj^{++} \ S \ T$ **and**
 $atms\text{-}of\text{-}mm \ (clauses_{NOT} \ S) \subseteq atms\text{-}of\text{-}ms \ A$ **and**
 $atm\text{-}of \ ' \ lits\text{-}of\text{-}l \ (trail \ S) \subseteq atms\text{-}of\text{-}ms \ A$ **and**
 $no\text{-}dup \ (trail \ S)$ **and**
 $inv \ S$
using $x\text{-}A$ **by** *auto*
then show $x \in ?B^+$ **unfolding** x
proof (*induction rule: tranclp-induct*)
case *base*
then show $?case$ **by** *auto*
next
case (*step* $T \ U$) **note** $step = this(1)$ **and** $ST = this(2)$ **and** $IH = this(3)[OF \ this(4-7)]$
and $N\text{-}A = this(4)$ **and** $M\text{-}A = this(5)$ **and** $nd = this(6)$ **and** $inv = this(7)$

have [*simp*]: $atms\text{-}of\text{-}mm \ (clauses_{NOT} \ S) = atms\text{-}of\text{-}mm \ (clauses_{NOT} \ T)$
using $step \ rtranclp\text{-}dpll\text{-}bj\text{-}atms\text{-}of\text{-}ms\text{-}clauses\text{-}inv \ tranclp\text{-}into\text{-}rtranclp \ inv$ **by** *fastforce*
have $no\text{-}dup \ (trail \ T)$
using $local.step \ nd \ rtranclp\text{-}dpll\text{-}bj\text{-}no\text{-}dup \ tranclp\text{-}into\text{-}rtranclp \ inv$ **by** *fastforce*
moreover have $atm\text{-}of \ ' \ (lits\text{-}of\text{-}l \ (trail \ T)) \subseteq atms\text{-}of\text{-}ms \ A$
by (*metis* $inv \ M\text{-}A \ N\text{-}A \ local.step \ rtranclp\text{-}dpll\text{-}bj\text{-}atms\text{-}in\text{-}trail\text{-}in\text{-}set \ tranclp\text{-}into\text{-}rtranclp$)
moreover have $inv \ T$
using $inv \ local.step \ rtranclp\text{-}dpll\text{-}bj\text{-}inv \ tranclp\text{-}into\text{-}rtranclp$ **by** *fastforce*
ultimately have $(U, \ T) \in ?B$ **using** $ST \ N\text{-}A \ M\text{-}A \ inv$ **by** *auto*
then show $?case$ **using** IH **by** (*rule* $trancl\text{-}into\text{-}trancl2$)
qed
qed

lemma *wf-tranclp-dpll-bj*:
assumes fin : *finite* A
shows $wf \ \{(T, \ S). \ dpll\text{-}bj^{++} \ S \ T$
 $\wedge atms\text{-}of\text{-}mm \ (clauses_{NOT} \ S) \subseteq atms\text{-}of\text{-}ms \ A \wedge atm\text{-}of \ ' \ lits\text{-}of\text{-}l \ (trail \ S) \subseteq atms\text{-}of\text{-}ms \ A$
 $\wedge no\text{-}dup \ (trail \ S) \wedge inv \ S\}$
using $wf\text{-}trancl[OF \ wf\text{-}dpll\text{-}bj[OF \ fin]] \ rtranclp\text{-}dpll\text{-}bj\text{-}inv\text{-}incl\text{-}dpll\text{-}bj\text{-}inv\text{-}trancl$
by (*rule* $wf\text{-}subset$)

lemma *dpll-bj-sat-ext-iff*:
 $dpll\text{-}bj \ S \ T \implies inv \ S \implies I \models_{sextm \ clauses_{NOT}} S \longleftrightarrow I \models_{sextm \ clauses_{NOT}} T$
by (*simp* add : $dpll\text{-}bj\text{-}clauses$)

lemma *rtranclp-dpll-bj-sat-ext-iff*:
 $dpll\text{-}bj^{**} \ S \ T \implies inv \ S \implies I \models_{sextm \ clauses_{NOT}} S \longleftrightarrow I \models_{sextm \ clauses_{NOT}} T$
by (*induction rule: rtranclp-induct*) (*simp* all add : $rtranclp\text{-}dpll\text{-}bj\text{-}inv \ dpll\text{-}bj\text{-}sat\text{-}ext\text{-}iff$)

theorem *full-dpll-backjump-final-state*:
fixes $A :: 'v \ clause \ set$ **and** $S \ T :: 'st$
assumes
 $full$: $full \ dpll\text{-}bj \ S \ T$ **and**
 $atms\text{-}S$: $atms\text{-}of\text{-}mm \ (clauses_{NOT} \ S) \subseteq atms\text{-}of\text{-}ms \ A$ **and**
 $atms\text{-}trail$: $atm\text{-}of \ ' \ lits\text{-}of\text{-}l \ (trail \ S) \subseteq atms\text{-}of\text{-}ms \ A$ **and**
 $n\text{-}d$: $no\text{-}dup \ (trail \ S)$ **and**
 $finite \ A$ **and**
 inv : $inv \ S$ **and**
 $decomp$: $all\text{-}decomposition\text{-}implies\text{-}m \ (clauses_{NOT} \ S) \ (get\text{-}all\text{-}ann\text{-}decomposition \ (trail \ S))$
shows $unsatisfiable \ (set\text{-}mset \ (clauses_{NOT} \ S))$
 $\vee (trail \ T \models_{asm \ clauses_{NOT}} S \wedge satisfiable \ (set\text{-}mset \ (clauses_{NOT} \ S)))$

proof –

have st : $dpll\text{-}bj^{**} \ S \ T$ **and** $no\text{-}step \ dpll\text{-}bj \ T$
using $full \ unfolding \ full\text{-}def$ **by** $fast+$
moreover **have** $atms\text{-}of\text{-}mm \ (clauses_{NOT} \ T) \subseteq atms\text{-}of\text{-}ms \ A$
using $atms\text{-}S \ inv \ rtranclp\text{-}dpll\text{-}bj\text{-}atms\text{-}of\text{-}ms\text{-}clauses\text{-}inv \ st$ **by** $blast$
moreover **have** $atm\text{-}of \ ' \ lits\text{-}of\text{-}l \ (trail \ T) \subseteq atms\text{-}of\text{-}ms \ A$
using $atms\text{-}S \ atms\text{-}trail \ inv \ rtranclp\text{-}dpll\text{-}bj\text{-}atms\text{-}in\text{-}trail\text{-}in\text{-}set \ st$ **by** $auto$
moreover **have** $no\text{-}dup \ (trail \ T)$
using $n\text{-}d \ inv \ rtranclp\text{-}dpll\text{-}bj\text{-}no\text{-}dup \ st$ **by** $blast$
moreover **have** inv : $inv \ T$
using $inv \ rtranclp\text{-}dpll\text{-}bj\text{-}inv \ st$ **by** $blast$
moreover
have $decomp$: $all\text{-}decomposition\text{-}implies\text{-}m \ (clauses_{NOT} \ T) \ (get\text{-}all\text{-}ann\text{-}decomposition \ (trail \ T))$
using $\langle inv \ S \rangle \ decomp \ rtranclp\text{-}dpll\text{-}bj\text{-}all\text{-}decomposition\text{-}implies\text{-}inv \ st$ **by** $blast$
ultimately **have** $unsatisfiable \ (set\text{-}mset \ (clauses_{NOT} \ T))$
 $\vee \ (trail \ T \models_{asm} clauses_{NOT} \ T \wedge satisfiable \ (set\text{-}mset \ (clauses_{NOT} \ T)))$
using $\langle finite \ A \rangle \ dpll\text{-}backjump\text{-}final\text{-}state$ **by** $force$
then show $?thesis$
by $(meson \ \langle inv \ S \rangle \ rtranclp\text{-}dpll\text{-}bj\text{-}sat\text{-}iff \ satisfiable\text{-}carac \ st \ true\text{-}annots\text{-}true\text{-}cls)$
qed

corollary $full\text{-}dpll\text{-}backjump\text{-}final\text{-}state\text{-}from\text{-}init\text{-}state$:

fixes $A :: 'v \ clause \ set$ **and** $S \ T :: 'st$
assumes
 $full$: $full \ dpll\text{-}bj \ S \ T$ **and**
 $trail \ S = []$ **and**
 $clauses_{NOT} \ S = N$ **and**
 $inv \ S$
shows $unsatisfiable \ (set\text{-}mset \ N) \vee (trail \ T \models_{asm} N \wedge satisfiable \ (set\text{-}mset \ N))$
using $assms \ full\text{-}dpll\text{-}backjump\text{-}final\text{-}state[of \ S \ T \ set\text{-}mset \ N]$ **by** $auto$

lemma $tranclp\text{-}dpll\text{-}bj\text{-}trail\text{-}mes\text{-}decreasing\text{-}prop$:

assumes $dpll$: $dpll\text{-}bj^{++} \ S \ T$ **and** inv : $inv \ S$ **and**
 $N\text{-}A$: $atms\text{-}of\text{-}mm \ (clauses_{NOT} \ S) \subseteq atms\text{-}of\text{-}ms \ A$ **and**
 $M\text{-}A$: $atm\text{-}of \ ' \ lits\text{-}of\text{-}l \ (trail \ S) \subseteq atms\text{-}of\text{-}ms \ A$ **and**
 $n\text{-}d$: $no\text{-}dup \ (trail \ S)$ **and**
 $fin\text{-}A$: $finite \ A$
shows $(2 + card \ (atms\text{-}of\text{-}ms \ A)) \wedge (1 + card \ (atms\text{-}of\text{-}ms \ A))$
 $\quad - \mu_C \ (1 + card \ (atms\text{-}of\text{-}ms \ A)) \ (2 + card \ (atms\text{-}of\text{-}ms \ A)) \ (trail\text{-}weight \ T)$
 $\quad < (2 + card \ (atms\text{-}of\text{-}ms \ A)) \wedge (1 + card \ (atms\text{-}of\text{-}ms \ A))$
 $\quad - \mu_C \ (1 + card \ (atms\text{-}of\text{-}ms \ A)) \ (2 + card \ (atms\text{-}of\text{-}ms \ A)) \ (trail\text{-}weight \ S)$
using $dpll$

proof ($induction$)

case $base$

then show $?case$

using $N\text{-}A \ M\text{-}A \ n\text{-}d \ dpll\text{-}bj\text{-}trail\text{-}mes\text{-}decreasing\text{-}prop \ fin\text{-}A \ inv$ **by** $blast$

next

case $(step \ T \ U)$ **note** $st = this(1)$ **and** $dpll = this(2)$ **and** $IH = this(3)$

have $atms\text{-}of\text{-}mm \ (clauses_{NOT} \ S) = atms\text{-}of\text{-}mm \ (clauses_{NOT} \ T)$

using $rtranclp\text{-}dpll\text{-}bj\text{-}atms\text{-}of\text{-}ms\text{-}clauses\text{-}inv$ **by** $(metis \ dpll\text{-}bj\text{-}clauses \ dpll\text{-}bj\text{-}inv \ inv \ st \ tranclpD)$

then have $N\text{-}A'$: $atms\text{-}of\text{-}mm \ (clauses_{NOT} \ T) \subseteq atms\text{-}of\text{-}ms \ A$

using $N\text{-}A$ **by** $auto$

moreover **have** $M\text{-}A'$: $atm\text{-}of \ ' \ lits\text{-}of\text{-}l \ (trail \ T) \subseteq atms\text{-}of\text{-}ms \ A$

by $(meson \ M\text{-}A \ N\text{-}A \ inv \ rtranclp\text{-}dpll\text{-}bj\text{-}atms\text{-}in\text{-}trail\text{-}in\text{-}set \ st \ dpll \ tranclp.r\text{-}into\text{-}trancl \ tranclp\text{-}into\text{-}rtranclp \ tranclp\text{-}trans)$

```

moreover have nd: no-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 — End of *dpll-with-backjumping*

5.2.4 CDCL

In this section we will now define the conflict driven clause learning above DPLL: we first introduce the rules learn and forget, and the add these rules to the DPLL calculus.

Learn and Forget

Learning adds a new clause where all the literals are already included in the clauses.

```

locale learn-ops =
  dpll-state trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT
for
  trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
  clausesNOT :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  remove-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st +
fixes
  learn-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool
begin
inductive learn :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
learnNOT-rule: clausesNOT S  $\models_{pm}$  C  $\Rightarrow$ 
atms-of C  $\subseteq$  atms-of-mm (clausesNOT S)  $\cup$  atm-of ' (lits-of-l (trail S))  $\Rightarrow$ 
learn-cond C S  $\Rightarrow$ 
T  $\sim$  add-clNOT C S  $\Rightarrow$ 
learn S T
inductive-cases learnNOTE: learn S T

```

```

lemma learn- $\mu_C$ -stable:
  assumes learn S T and no-dup (trail S)
  shows  $\mu_C A B (trail\text{-}weight\ S) = \mu_C A B (trail\text{-}weight\ T)$ 
  using assms by (auto elim: learnNOTE)
end

```

Forget removes an information that can be deduced from the context (e.g. redundant clauses, tautologies)

```

locale forget-ops =
  dpll-state trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT
for
  trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
  clausesNOT :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and

```



```

    remove-clsNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st +
fixes
    forget-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool
begin
inductive forgetNOT :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
forgetNOT:
    removeAll-mset C(clausesNOT S)  $\models_{pm}$  C  $\Rightarrow$ 
    forget-cond C S  $\Rightarrow$ 
    C  $\in \#$  clausesNOT S  $\Rightarrow$ 
    T  $\sim$  remove-clsNOT C S  $\Rightarrow$ 
    forgetNOT S T
inductive-cases forgetNOTE: forgetNOT S T

lemma forget- $\mu_C$ -stable:
    assumes forgetNOT S T
    shows  $\mu_C$  A B (trail-weight S) =  $\mu_C$  A B (trail-weight T)
    using assms by (auto elim!: forgetNOTE)
end

locale learn-and-forgetNOT =
    learn-ops trail clausesNOT prepend-trail tl-trail add-clsNOT remove-clsNOT learn-cond +
    forget-ops trail clausesNOT prepend-trail tl-trail add-clsNOT remove-clsNOT forget-cond
for
    trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
    clausesNOT :: 'st  $\Rightarrow$  'v clauses and
    prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
    tl-trail :: 'st  $\Rightarrow$  'st and
    add-clsNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
    remove-clsNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
    learn-cond forget-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool
begin
inductive learn-and-forgetNOT :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool
where
lf-learn: learn S T  $\Rightarrow$  learn-and-forgetNOT S T |
lf-forget: forgetNOT S T  $\Rightarrow$  learn-and-forgetNOT S T
end

```

Definition of CDCL

```

locale conflict-driven-clause-learning-ops =
    dpll-with-backjumping-ops trail clausesNOT prepend-trail tl-trail add-clsNOT remove-clsNOT
    inv backjump-conds propagate-conds +
    learn-and-forgetNOT trail clausesNOT prepend-trail tl-trail add-clsNOT remove-clsNOT learn-cond
    forget-cond
for
    trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
    clausesNOT :: 'st  $\Rightarrow$  'v clauses and
    prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
    tl-trail :: 'st  $\Rightarrow$  'st and
    add-clsNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
    remove-clsNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
    inv :: 'st  $\Rightarrow$  bool and
    backjump-conds :: 'v clause  $\Rightarrow$  'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool and
    propagate-conds :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  bool and
    learn-cond forget-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool
begin

```

inductive $cdcl_{NOT} :: 'st \Rightarrow 'st \Rightarrow bool$ **for** $S :: 'st$ **where**
c-dpll-bj: $dpll\text{-}bj\ S\ S' \Longrightarrow cdcl_{NOT}\ S\ S' \mid$
c-learn: $learn\ S\ S' \Longrightarrow cdcl_{NOT}\ S\ S' \mid$
c-forget_{NOT}: $forget_{NOT}\ S\ S' \Longrightarrow cdcl_{NOT}\ S\ S'$

lemma $cdcl_{NOT}\text{-all-induct}[consumes\ 1, case\text{-}names\ dpll\text{-}bj\ learn\ forget_{NOT}]$:

fixes $S\ T :: 'st$

assumes $cdcl_{NOT}\ S\ T$ **and**

$dpll: \bigwedge T. dpll\text{-}bj\ S\ T \Longrightarrow P\ S\ T$ **and**

learning:

$\bigwedge C\ T. clauses_{NOT}\ S \models_{pm} C \Longrightarrow$

$atms\text{-}of\ C \subseteq atms\text{-}of\text{-}mm\ (clauses_{NOT}\ S) \cup atm\text{-}of\ ' (lits\text{-}of\text{-}l\ (trail\ S)) \Longrightarrow$

$T \sim add\text{-}cls_{NOT}\ C\ S \Longrightarrow$

$P\ S\ T$ **and**

forgetting: $\bigwedge C\ T. removeAll\text{-}mset\ C\ (clauses_{NOT}\ S) \models_{pm} C \Longrightarrow$

$C \in \# clauses_{NOT}\ S \Longrightarrow$

$T \sim remove\text{-}cls_{NOT}\ C\ S \Longrightarrow$

$P\ S\ T$

shows $P\ S\ T$

using $assms(1)$ **by** (*induction rule*: $cdcl_{NOT}.induct$)

(*auto intro*: $assms(2, 3, 4)$ *elim!*: $learn_{NOT}E\ forget_{NOT}E$) $+$

lemma $cdcl_{NOT}\text{-no-dup}$:

assumes

$cdcl_{NOT}\ S\ T$ **and**

inv S **and**

no-dup ($trail\ S$)

shows *no-dup* ($trail\ T$)

using $assms$ **by** (*induction rule*: $cdcl_{NOT}\text{-all-induct}$) (*auto intro*: $dpll\text{-}bj\text{-no-dup}$)

Consistency of the trail lemma $cdcl_{NOT}\text{-consistent}$:

assumes

$cdcl_{NOT}\ S\ T$ **and**

inv S **and**

no-dup ($trail\ S$)

shows *consistent-interp* ($lits\text{-}of\text{-}l\ (trail\ T)$)

using $cdcl_{NOT}\text{-no-dup}[OF\ assms]$ *distinct-consistent-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 means that some variable of the trail might not be present in the clauses anymore.

lemma $cdcl_{NOT}\text{-atms-of-ms-clauses-decreasing}$:

assumes $cdcl_{NOT}\ S\ T$ **and** *inv* S **and** *no-dup* ($trail\ S$)

shows $atms\text{-}of\text{-}mm\ (clauses_{NOT}\ T) \subseteq atms\text{-}of\text{-}mm\ (clauses_{NOT}\ S) \cup atm\text{-}of\ ' (lits\text{-}of\text{-}l\ (trail\ S))$

using $assms$ **by** (*induction rule*: $cdcl_{NOT}\text{-all-induct}$)

(*auto dest!*: $dpll\text{-}bj\text{-atms-of-ms-clauses-inv}\ set\text{-}mp\ simp\ add: atms\text{-}of\text{-}ms\text{-}def\ Union\text{-}eq$)

lemma $cdcl_{NOT}\text{-atms-in-trail}$:

assumes $cdcl_{NOT}\ S\ T$ **and** *inv* S **and** *no-dup* ($trail\ S$)

and $atm\text{-}of\ ' (lits\text{-}of\text{-}l\ (trail\ S)) \subseteq atms\text{-}of\text{-}mm\ (clauses_{NOT}\ S)$

shows $atm\text{-}of\ ' (lits\text{-}of\text{-}l\ (trail\ T)) \subseteq atms\text{-}of\text{-}mm\ (clauses_{NOT}\ S)$

using $assms$ **by** (*induction rule*: $cdcl_{NOT}\text{-all-induct}$) (*auto simp add*: $dpll\text{-}bj\text{-atms-in-trail}$)

lemma $cdcl_{NOT}\text{-atms-in-trail-in-set}$:

```

assumes
   $cdcl_{NOT} S T$  and  $inv S$  and  $no\_dup (trail S)$  and
   $atms\_of\_mm (clauses_{NOT} S) \subseteq A$  and
   $atm\_of \text{ ' } (lits\_of\_l (trail S)) \subseteq A$ 
shows  $atm\_of \text{ ' } (lits\_of\_l (trail T)) \subseteq A$ 
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  $cdcl_{NOT} S T$  and  $inv S$  and  $n\_d[simp]: no\_dup (trail S)$  and
   $all\_decomposition\_implies\_m (clauses_{NOT} S) (get\_all\_ann\_decomposition (trail S))$ 
shows
   $all\_decomposition\_implies\_m (clauses_{NOT} T) (get\_all\_ann\_decomposition (trail T))$ 
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 ( $forget_{NOT} C T$ ) note  $cls\_C = this(1)$  and  $C = this(2)$  and  $T = this(3)$  and  $inv = this(4)$ 
and
   $decomp = this(5)$ 
show ?case
  unfolding all-decomposition-implies-def Ball-def
proof (intro allI, clarify)
  fix  $a b$ 
  assume  $(a, b) \in set (get\_all\_ann\_decomposition (trail T))$ 
  then have  $unmark\_l a \cup set\_mset (clauses_{NOT} S) \models_{ps} unmark\_l b$ 
    using  $decomp T$  by (auto simp add: all-decomposition-implies-def)
  moreover
    have  $a1:C \in set\_mset (clauses_{NOT} S)$ 
      using  $C$  by blast
    have  $clauses_{NOT} T = clauses_{NOT} (remove\_cls_{NOT} C S)$ 
      using  $T state\_eq_{NOT}\text{-}clauses$  by blast
    then have  $set\_mset (clauses_{NOT} T) \models_{ps} set\_mset (clauses_{NOT} S)$ 
      using  $a1$  by (metis (no-types) clauses-remove-clsNOT cls-C insert-Diff order-refl
        set-mset-minus-replicate-mset(1) true-clss-clss-def true-clss-clss-insert)
    ultimately show  $unmark\_l a \cup set\_mset (clauses_{NOT} T) \models_{ps} unmark\_l b$ 
      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 $I \models_{sextm} clauses_{NOT} S \longleftrightarrow I \models_{sextm} clauses_{NOT} T$
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** $T = this(3)$

```

{ fix J
  assume
     $I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} S$  and
     $I \subseteq J$  and
    tot: total-over-m  $J$  (set-mset ( $\{\#C\# \} + \text{clauses}_{\text{NOT}} S$ )) and
    cons: consistent-interp  $J$ 
  then have  $J \models_{\text{sm}} \text{clauses}_{\text{NOT}} S$  unfolding true-clss-ext-def by auto

  moreover
    with  $\langle \text{clauses}_{\text{NOT}} S \models_{\text{pm}} C \rangle$  have  $J \models C$ 
    using tot cons unfolding true-clss-clss-def by auto
    ultimately have  $J \models_{\text{sm}} \{\#C\# \} + \text{clauses}_{\text{NOT}} S$  by auto
}
then have  $H: I \models_{\text{sextm}} (\text{clauses}_{\text{NOT}} S) \implies I \models_{\text{sext}} \text{insert } C (\text{set-mset } (\text{clauses}_{\text{NOT}} S))$ 
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 (forgetNOT  $C$   $T$ ) note cls-C = this(1) and  $T = \text{this}(3)$ 
{ fix J
  assume
     $I \models_{\text{sext}} \text{set-mset } (\text{clauses}_{\text{NOT}} S) - \{C\}$  and
     $I \subseteq J$  and
    tot: total-over-m  $J$  (set-mset ( $\text{clauses}_{\text{NOT}} S$ )) and
    cons: consistent-interp  $J$ 
  then have  $J \models_{\text{s}} \text{set-mset } (\text{clauses}_{\text{NOT}} S) - \{C\}$ 
    unfolding true-clss-ext-def by (meson Diff-subset total-over-m-subset)

  moreover
    with cls-C have  $J \models C$ 
    using tot cons unfolding true-clss-clss-def
    by (metis Un-commute forgetNOT.hyps(2) insert-Diff insert-is-Un order-refl
      set-mset-minus-replicate-mset(1))
    ultimately have  $J \models_{\text{sm}} (\text{clauses}_{\text{NOT}} S)$  by (metis insert-Diff-single true-clss-insert)
  }
  then have  $H: I \models_{\text{sext}} \text{set-mset } (\text{clauses}_{\text{NOT}} S) - \{C\} \implies I \models_{\text{sextm}} (\text{clauses}_{\text{NOT}} S)$ 
    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

```

CDCL with invariant

```

locale conflict-driven-clause-learning =
  conflict-driven-clause-learning-ops +
  assumes cdclNOT-inv:  $\bigwedge S T. \text{cdcl}_{\text{NOT}} S T \implies \text{inv } S \implies \text{inv } T$ 
begin
sublocale dpll-with-backjumping
apply unfold-locales
using cdclNOT.simps cdclNOT-inv by auto

```

lemma *rtrancpl-cdcl_{NOT}-inv*:

*cdcl_{NOT}** S T \implies inv S \implies inv T*

by (induction rule: rtrancpl-induct) (auto simp add: cdcl_{NOT}-inv)

lemma *rtrancpl-cdcl_{NOT}-no-dup*:

*assumes cdcl_{NOT}** S T and inv S*

and no-dup (trail S)

shows no-dup (trail T)

using assms by (induction rule: rtrancpl-induct) (auto intro: cdcl_{NOT}-no-dup rtrancpl-cdcl_{NOT}-inv)

lemma *rtrancpl-cdcl_{NOT}-trail-clauses-bound*:

assumes

*cdcl: cdcl_{NOT}** S T and*

inv: inv S and

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

atms-clauses-S: atms-of-mm (clauses_{NOT} S) \subseteq A and

atms-trail-S: atm-of (lits-of-l (trail S)) \subseteq A

shows atm-of (lits-of-l (trail T)) \subseteq A \wedge atms-of-mm (clauses_{NOT} T) \subseteq A

using cdcl

proof *(induction rule: rtrancpl-induct)*

case base

then show ?case using atms-clauses-S atms-trail-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 rtrancpl-cdcl_{NOT}-inv by blast

have no-dup (trail T)

using rtrancpl-cdcl_{NOT}-no-dup[of S T] st cdcl_{NOT} inv n-d by blast

then have atms-of-mm (clauses_{NOT} U) \subseteq A

using cdcl_{NOT}-atms-of-ms-clauses-decreasing[OF cdcl_{NOT}] IH n-d (inv T) by fast

moreover

have atm-of (lits-of-l (trail U)) \subseteq A

using cdcl_{NOT}-atms-in-trail-in-set[OF cdcl_{NOT}, of A] (no-dup (trail T))

by (meson atms-trail-S atms-clauses-S IH (inv T) cdcl_{NOT})

ultimately show ?case by fast

qed

lemma *rtrancpl-cdcl_{NOT}-all-decomposition-implies*:

*assumes cdcl_{NOT}** S T and inv S and no-dup (trail S) and*

all-decomposition-implies-m (clauses_{NOT} S) (get-all-ann-decomposition (trail S))

shows

all-decomposition-implies-m (clauses_{NOT} T) (get-all-ann-decomposition (trail T))

using assms by (induction)

(auto intro: rtrancpl-cdcl_{NOT}-inv cdcl_{NOT}-all-decomposition-implies rtrancpl-cdcl_{NOT}-no-dup)

lemma *rtrancpl-cdcl_{NOT}-bj-sat-ext-iff*:

*assumes cdcl_{NOT}** S T and inv S and no-dup (trail S)*

shows $I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} S \longleftrightarrow I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} T$

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 (finite A \wedge inv S \wedge atms-of-mm (clauses_{NOT} S) \subseteq atms-of-ms A
 \wedge atm-of (lits-of-l (trail S)) \subseteq atms-of-ms A \wedge no-dup (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**
 $learn-or-forget S T \equiv learn S T \vee forget_{NOT} S T$

lemma *rtrancpl-learn-or-forget-cdcl_{NOT}*:
 $learn-or-forget^{**} S T \implies cdcl_{NOT}^{**} S T$
using *rtrancpl-mono[of learn-or-forget cdcl_{NOT}]* **by** (*blast intro: cdcl_{NOT.c-learn} cdcl_{NOT.c-forget_{NOT}}*)

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 $(2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))$
 $- \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight U)$
 $< (2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))$
 $- \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight S)$
(is ? μ U < ? μ S)

proof –

have $? \mu S = ? \mu T$

using *l-f*

proof (*induction*)

case *base*

then show *?case* **by** *simp*

next

case (*step T U*)

moreover then have *no-dup (trail T)*

using *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 *?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 *?thesis*

using *dpll-bj-trail-mes-decreasing-prop[of T U A, OF dpll] finite*

unfolding *cdcl_{NOT-NOT-all-inv-def}* **by** *presburger*

qed

lemma *infinite-cdcl_{NOT}-exists-learn-and-forget-infinite-chain*:

assumes

$\bigwedge i. cdcl_{NOT} (f i) (f (Suc i))$ **and**

inv: cdcl_{NOT-NOT-all-inv} A (f 0)

shows $\exists j. \forall i \geq j. learn-or-forget (f i) (f (Suc i))$

using *assms*

proof (*induction (2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))*)

$- \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight (f 0))$

arbitrary: f

rule: nat-less-induct-case)

case (*Suc n*) **note** $IH = this(1)$ **and** $\mu = this(2)$ **and** $cdcl_{NOT} = this(3)$ **and** $inv = this(4)$

consider

(*dpll-end*) $\exists j. \forall i \geq j. learn-or-forget (f i) (f (Suc i))$

```

| (dpll-more)  $\neg(\exists j. \forall i \geq j. \text{learn-or-forget } (f \ i) \ (f \ (\text{Suc } i)))$ 
by blast
then show ?case
proof cases
  case dpll-end
  then show ?thesis by auto
next
case dpll-more
then have j:  $\exists i. \neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f \ i) \ (f \ (\text{Suc } i))$ 
  by blast
obtain i where
 $\neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f \ i) \ (f \ (\text{Suc } i))$  and
 $\forall k < i. \text{learn-or-forget } (f \ k) \ (f \ (\text{Suc } k))$ 
proof -
  obtain i0 where  $\neg \text{learn } (f \ i_0) \ (f \ (\text{Suc } i_0)) \wedge \neg \text{forget}_{NOT} (f \ i_0) \ (f \ (\text{Suc } i_0))$ 
    using j by auto
  then have {i.  $i \leq i_0 \wedge \neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f \ i) \ (f \ (\text{Suc } i))$ }  $\neq \{\}$ 
    by auto
  let ?I = {i.  $i \leq i_0 \wedge \neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f \ i) \ (f \ (\text{Suc } i))$ }
  let ?i = Min ?I
  have finite ?I
    by auto
  have  $\neg \text{learn } (f \ ?i) \ (f \ (\text{Suc } ?i)) \wedge \neg \text{forget}_{NOT} (f \ ?i) \ (f \ (\text{Suc } ?i))$ 
    using Min-in[OF ⟨finite ?I⟩ ⟨?I  $\neq \{\}$ ⟩] by auto
  moreover have  $\forall k < ?i. \text{learn-or-forget } (f \ k) \ (f \ (\text{Suc } k))$ 
    using Min.coboundedI[of {i.  $i \leq i_0 \wedge \neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f \ i) \ (f \ (\text{Suc } i))$ }, simplified]
    by (meson  $\neg \text{learn } (f \ i_0) \ (f \ (\text{Suc } i_0)) \wedge \neg \text{forget}_{NOT} (f \ i_0) \ (f \ (\text{Suc } i_0))$ ) less-imp-le
    dual-order.trans not-le
  ultimately show ?thesis using that by blast
qed
def g  $\equiv \lambda n. f \ (n + \text{Suc } i)$ 
have dpll-bj (f i) (g 0)
  using  $\neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{NOT} (f \ i) \ (f \ (\text{Suc } i))$  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 rtranclp.simps
       $\langle \forall k < i. \text{learn } (f \ k) \ (f \ (\text{Suc } k)) \vee \text{forget}_{NOT} (f \ k) \ (f \ (\text{Suc } k)) \rangle$ )
}
then have learn-or-forget** (f 0) (f i) by blast
then have  $(2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$ 
   $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } (g \ 0))$ 
 $< (2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))$ 
   $- \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } (f \ 0))$ 
  using 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 rtranclp-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  $\bigwedge i. \text{cdcl}_{NOT} (g \ i) \ (g \ (\text{Suc } i))$ 

```

```

    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:  $\bigwedge i. i \geq j \implies \text{learn-or-forget } (g \ i) \ (g \ (\text{Suc } i))$ 
    using IH unfolding  $\mu[\text{symmetric}]$  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  $\forall k \geq j + \text{Suc } i. \text{learn-or-forget } (f \ k) \ (f \ (\text{Suc } k))$ 
      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:  $\exists i. \neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{\text{NOT}} (f \ i) \ (f \ (\text{Suc } i))$ 
    by blast
  obtain i where
     $\neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{\text{NOT}} (f \ i) \ (f \ (\text{Suc } i))$  and
     $\forall k < i. \text{learn-or-forget } (f \ k) \ (f \ (\text{Suc } k))$ 
  proof -
    obtain i0 where  $\neg \text{learn } (f \ i_0) \ (f \ (\text{Suc } i_0)) \wedge \neg \text{forget}_{\text{NOT}} (f \ i_0) \ (f \ (\text{Suc } i_0))$ 
      using j by auto
    then have  $\{i. i \leq i_0 \wedge \neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{\text{NOT}} (f \ i) \ (f \ (\text{Suc } i))\} \neq \{\}$ 
      by auto
    let ?I =  $\{i. i \leq i_0 \wedge \neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{\text{NOT}} (f \ i) \ (f \ (\text{Suc } i))\}$ 
    let ?i = Min ?I
    have finite ?I
      by auto
    have  $\neg \text{learn } (f \ ?i) \ (f \ (\text{Suc } ?i)) \wedge \neg \text{forget}_{\text{NOT}} (f \ ?i) \ (f \ (\text{Suc } ?i))$ 
      using Min-in[OF (finite ?I) (?I  $\neq \{\}$ )] by auto
    moreover have  $\forall k < ?i. \text{learn-or-forget } (f \ k) \ (f \ (\text{Suc } k))$ 
      using Min.coboundedI[of  $\{i. i \leq i_0 \wedge \neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{\text{NOT}} (f \ i) \ (f \ (\text{Suc } i))\}$ , simplified]
      by (meson  $\neg \text{learn } (f \ i_0) \ (f \ (\text{Suc } i_0)) \wedge \neg \text{forget}_{\text{NOT}} (f \ i_0) \ (f \ (\text{Suc } i_0))$ ) less-imp-le
      dual-order.trans not-le
    ultimately show ?thesis using that by blast
  qed
  have dpll-bj (f i) (f (Suc i))
    using  $\neg \text{learn } (f \ i) \ (f \ (\text{Suc } i)) \wedge \neg \text{forget}_{\text{NOT}} (f \ i) \ (f \ (\text{Suc } i))$  cdclNOT cdclNOT.cases
    by blast
  {
    fix j
    assume  $j \leq i$ 
    then have learn-or-forget** (f 0) (f j)
      apply (induction j)
      apply simp
      by (metis (no-types, lifting) Suc-leD Suc-le-lessD rtrancpl.simps
         $\langle \forall k < i. \text{learn } (f \ k) \ (f \ (\text{Suc } k)) \vee \text{forget}_{\text{NOT}} (f \ k) \ (f \ (\text{Suc } k)) \rangle$ )
  }

```



```

}
then have learn-or-forget** (f 0) (f i) by blast

then show False
  using learn-or-forget-dpll- $\mu_C$ [of f 0 f i f (Suc i) A] inv 0
  ⟨dpll-bj (f i) (f (Suc i))⟩ unfolding cdclNOT-NOT-all-inv-def by linarith
qed
qed

```

lemma wf-cdcl_{NOT}-no-learn-and-forget-infinite-chain:

```

assumes
  no-infinite-lf:  $\bigwedge f j. \neg (\forall i \geq j. \text{learn-or-forget } (f i) (f (Suc i)))$ 
shows wf {(T, S). cdclNOT S T  $\wedge$  cdclNOT-NOT-all-inv A S}
  (is wf {(T, S). cdclNOT S T  $\wedge$  ?inv S})
unfolding wf-iff-no-infinite-down-chain
proof (rule ccontr)
  assume  $\neg \neg (\exists f. \forall i. (f (Suc i), f i) \in \{(T, S). \text{cdcl}_{NOT} S T \wedge ?inv S\})$ 
  then obtain f where
     $\forall i. \text{cdcl}_{NOT} (f i) (f (Suc i)) \wedge ?inv (f i)$ 
  by fast
  then have  $\exists j. \forall i \geq j. \text{learn-or-forget } (f i) (f (Suc i))$ 
    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-tranclp-cdcl_{NOT}-tranclp-cdcl_{NOT}-and-inv:

```

cdclNOT++ S T  $\wedge$  cdclNOT-NOT-all-inv A S  $\longleftrightarrow$  ( $\lambda S T. \text{cdcl}_{NOT} S T \wedge \text{cdcl}_{NOT}$ -NOT-all-inv A
S)++ S T
(is ?A  $\wedge$  ?I  $\longleftrightarrow$  ?B)
proof
  assume ?A  $\wedge$  ?I
  then have ?A and ?I by blast+
  then show ?B
    apply induction
    apply (simp add: tranclp.r-into-trancl)
    by (subst tranclp.simps) (auto intro: cdclNOT-NOT-all-inv tranclp-into-rtranclp)
next
  assume ?B
  then have ?A by induction auto
  moreover have ?I using ⟨?B⟩ tranclpD by fastforce
  ultimately show ?A  $\wedge$  ?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). cdclNOT++ S T  $\wedge$  cdclNOT-NOT-all-inv A S}
using wf-trancl[OF wf-cdclNOT-no-learn-and-forget-infinite-chain[OF no-infinite-lf]]
apply (rule wf-subset)
by (auto simp: trancl-set-tranclp inv-and-tranclp-cdclNOT-tranclp-cdclNOT-and-inv)

```

lemma cdcl_{NOT}-final-state:

```

assumes
  n-s: no-step cdclNOT S and
  inv: cdclNOT-NOT-all-inv A S and
  decomp: all-decomposition-implies-m (clausesNOT S) (get-all-ann-decomposition (trail S))

```

shows *unsatisfiable* (*set-mset* (*clauses*_{NOT} *S*))
 \vee (*trail* *S* \models_{asm} *clauses*_{NOT} *S* \wedge *satisfiable* (*set-mset* (*clauses*_{NOT} *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*_{NOT} *S*) (*get-all-ann-decomposition* (*trail S*))

shows *unsatisfiable* (*set-mset* (*clauses*_{NOT} *T*))

\vee (*trail T* \models_{asm} *clauses*_{NOT} *T* \wedge *satisfiable* (*set-mset* (*clauses*_{NOT} *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*_{NOT} *T*) (*get-all-ann-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*

Termination

To prove termination we need to restrict learn and forget. Otherwise we could forget and relearn the exact same clause over and over. A first idea is to forbid removing clauses that can be used to backjump. This does not change the rules of the calculus. A second idea is to “merge” backjump and learn: that way, though closer to implementation, needs a change of the rules, since the backjump-rule learns the clause used to backjump.

Restricting learn and forget

locale *conflict-driven-clause-learning-learning-before-backjump-only-distinct-learnt* =

*dpll-state trail clauses*_{NOT} *prepend-trail tl-trail add-cls*_{NOT} *remove-cls*_{NOT} +
*conflict-driven-clause-learning trail clauses*_{NOT} *prepend-trail tl-trail add-cls*_{NOT} *remove-cls*_{NOT}
inv backjump-conds propagate-conds

$\lambda C S. \text{distinct-mset } C \wedge \neg \text{tautology } C \wedge \text{learn-restrictions } C S \wedge$

$(\exists F K d F' C' L. \text{trail } S = F' @ \text{Decided } K \# F \wedge C = C' + \{\#L\} \wedge F \models_{as} C \text{Not } C'$
 $\wedge C' + \{\#L\} \notin \# \text{ clauses}_{NOT} S)$

$\lambda C S. \neg (\exists F' F K d L. \text{trail } S = F' @ \text{Decided } K \# F \wedge F \models_{as} C \text{Not } (\text{remove1-mset } L C))$
 $\wedge \text{forget-restrictions } C S$

for

trail :: '*st* \Rightarrow (*v*, *unit*) *ann-lits* **and**

*clauses*_{NOT} :: '*st* \Rightarrow '*v* *clauses* **and**

prepend-trail :: (*v*, *unit*) *ann-lit* \Rightarrow '*st* \Rightarrow '*st* **and**

tl-trail :: '*st* \Rightarrow '*st* **and**

```

add-clsNOT :: 'v clause ⇒ 'st ⇒ 'st and
remove-clsNOT :: 'v clause ⇒ 'st ⇒ 'st and
inv :: 'st ⇒ bool and
backjump-conds :: 'v clause ⇒ 'v clause ⇒ 'v literal ⇒ 'st ⇒ 'st ⇒ bool and
propagate-conds :: ('v, unit) ann-lit ⇒ 'st ⇒ bool and
learn-restrictions forget-restrictions :: 'v clause ⇒ 'st ⇒ 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:  $\bigwedge T. \text{dpll-bj } S \ T \implies P \ S \ T$  and
learning:
 $\bigwedge C \ F \ K \ F' \ C' \ L \ T. \text{clauses}_{NOT} \ S \models_{pm} C \implies$ 
 $\text{atms-of } C \subseteq \text{atms-of-mm } (\text{clauses}_{NOT} \ S) \cup \text{atm-of ' (lits-of-l (trail } S)) \implies$ 
 $\text{distinct-mset } C \implies$ 
 $\neg \text{tautology } C \implies$ 
 $\text{learn-restrictions } C \ S \implies$ 
 $\text{trail } S = F' @ \text{Decided } K \ \# \ F \implies$ 
 $C = C' + \{\#L\# \} \implies$ 
 $F \models_{as} CNot \ C' \implies$ 
 $C' + \{\#L\# \} \notin \# \text{clauses}_{NOT} \ S \implies$ 
 $T \sim \text{add-cls}_{NOT} \ C \ S \implies$ 
 $P \ S \ T$  and
forgetting:  $\bigwedge C \ T. \text{removeAll-mset } C \ (\text{clauses}_{NOT} \ S) \models_{pm} C \implies$ 
 $C \in \# \text{clauses}_{NOT} \ S \implies$ 
 $\neg(\exists F' \ F \ K \ L. \text{trail } S = F' @ \text{Decided } K \ \# \ F \wedge F \models_{as} CNot \ (C - \{\#L\# \})) \implies$ 
 $T \sim \text{remove-cls}_{NOT} \ C \ S \implies$ 
 $\text{forget-restrictions } C \ S \implies$ 
 $P \ S \ T$ 
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  $\implies$  inv S  $\implies$  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 (clausesNOT T - clausesNOT S)
 $\subseteq$  simple-clss (atms-of-mm (clausesNOT S)  $\cup$  atm-of ' lits-of-l (trail S))
proof
fix C assume C: C  $\in$  set-mset (clausesNOT T - clausesNOT S)
have distinct-mset C  $\neg$ tautology C using learn C n-d by (elim learnNOTE; auto)+
then have C  $\in$  simple-clss (atms-of C)
using distinct-mset-not-tautology-implies-in-simple-clss by blast

```

moreover have $\text{atms-of } C \subseteq \text{atms-of-mm } (\text{clauses}_{NOT} S) \cup \text{atm-of ' lits-of-l } (\text{trail } S)$
using $\text{learn } C \text{ n-d by } (\text{elim learn}_{NOT} E) (\text{auto simp: atms-of-ms-def atms-of-def image-Un true-annots-CNot-all-atms-defined})$
moreover have $\text{finite } (\text{atms-of-mm } (\text{clauses}_{NOT} S) \cup \text{atm-of ' lits-of-l } (\text{trail } S))$
by auto
ultimately show $C \in \text{simple-clss } (\text{atms-of-mm } (\text{clauses}_{NOT} S) \cup \text{atm-of ' lits-of-l } (\text{trail } S))$
using $\text{simple-clss-mono by } (\text{metis (no-types) insert-subset mk-disjoint-insert})$
qed

definition $\text{conflicting-bj-clss } S \equiv$
 $\{C + \{\#L\# \} \mid C \text{ L. } C + \{\#L\# \} \in \# \text{ clauses}_{NOT} S \wedge \text{distinct-mset } (C + \{\#L\# \})$
 $\wedge \neg \text{tautology } (C + \{\#L\# \})$
 $\wedge (\exists F' K F. \text{trail } S = F' @ \text{Decided } K \# F \wedge F \models_{as} CNot C)\}$

lemma $\text{conflicting-bj-clss-remove-cl}_{NOT}[\text{simp}]$:
 $\text{conflicting-bj-clss } (\text{remove-cl}_{NOT} C S) = \text{conflicting-bj-clss } S - \{C\}$
unfolding $\text{conflicting-bj-clss-def by fastforce}$

lemma $\text{conflicting-bj-clss-remove-cl}_{NOT}'[\text{simp}]$:
 $T \sim \text{remove-cl}_{NOT} C S \implies \text{conflicting-bj-clss } T = \text{conflicting-bj-clss } S - \{C\}$
unfolding $\text{conflicting-bj-clss-def by fastforce}$

lemma $\text{conflicting-bj-clss-add-cl}_{NOT}\text{-state-eq}$:
assumes
 $T: T \sim \text{add-cl}_{NOT} C' S$ **and**
 $n\text{-d: no-dup } (\text{trail } S)$
shows $\text{conflicting-bj-clss } T$
 $= \text{conflicting-bj-clss } S$
 $\cup (\text{if } \exists C L. C' = C + \{\#L\# \} \wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$
 $\wedge (\exists F' K d F. \text{trail } S = F' @ \text{Decided } K \# F \wedge F \models_{as} CNot C)$
 $\text{then } \{C'\} \text{ else } \{\})$

proof –
def $P \equiv \lambda C L T. \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \}) \wedge$
 $(\exists F' K F. \text{trail } T = F' @ \text{Decided } K \# F \wedge F \models_{as} CNot C)$
have $\text{conf: } \bigwedge T. \text{conflicting-bj-clss } T = \{C + \{\#L\# \} \mid C L. C + \{\#L\# \} \in \# \text{ clauses}_{NOT} T \wedge P C L T\}$
unfolding $\text{conflicting-bj-clss-def } P\text{-def by auto}$
have $P\text{-S-T: } \bigwedge C L. P C L T = P C L S$
using $T \text{ n-d unfolding } P\text{-def by auto}$
have $P: \text{conflicting-bj-clss } T = \{C + \{\#L\# \} \mid C L. C + \{\#L\# \} \in \# \text{ clauses}_{NOT} S \wedge P C L T\} \cup$
 $\{C + \{\#L\# \} \mid C L. C + \{\#L\# \} \in \# \{\#C'\# \} \wedge P C L T\}$
using $T \text{ n-d unfolding conf by auto}$
moreover have $\{C + \{\#L\# \} \mid C L. C + \{\#L\# \} \in \# \text{ clauses}_{NOT} S \wedge P C L T\} = \text{conflicting-bj-clss } S$
using $T \text{ n-d unfolding } P\text{-def conflicting-bj-clss-def by auto}$
moreover have $\{C + \{\#L\# \} \mid C L. C + \{\#L\# \} \in \# \{\#C'\# \} \wedge P C L T\} =$
 $(\text{if } \exists C L. C' = C + \{\#L\# \} \wedge P C L S \text{ then } \{C'\} \text{ else } \{\})$
using $n\text{-d } T \text{ by (force simp: } P\text{-S-T)}$
ultimately show $?thesis \text{ unfolding } P\text{-def by presburger}$
qed

lemma $\text{conflicting-bj-clss-add-cl}_{NOT}$:
 $\text{no-dup } (\text{trail } S) \implies$
 $\text{conflicting-bj-clss } (\text{add-cl}_{NOT} C' S)$
 $= \text{conflicting-bj-clss } S$
 $\cup (\text{if } \exists C L. C' = C + \{\#L\# \} \wedge \text{distinct-mset } (C + \{\#L\# \}) \wedge \neg \text{tautology } (C + \{\#L\# \})$

$\wedge (\exists F' K d F. \text{trail } S = F' @ \text{Decided } K \# F \wedge F \models_{as} C \text{Not } C)$
 then $\{C'\}$ else $\{\}$)
using *conflicting-bj-clss-add-clss_{NOT}-state-eq* **by** *auto*

lemma *conflicting-bj-clss-incl-clauses*:
conflicting-bj-clss $S \subseteq \text{set-mset } (\text{clauses}_{NOT} S)$
unfolding *conflicting-bj-clss-def* **by** *auto*

lemma *finite-conflicting-bj-clss[simp]*:
finite (*conflicting-bj-clss* S)
using *conflicting-bj-clss-incl-clauses[of S]* *rev-finite-subset* **by** *blast*

lemma *learn-conflicting-increasing*:
no-dup (*trail* S) \implies *learn* $S T \implies$ *conflicting-bj-clss* $S \subseteq$ *conflicting-bj-clss* T
apply (*elim learn_{NOT}E*)
by (*subst conflicting-bj-clss-add-clss_{NOT}-state-eq*[*of T*]) *auto*

abbreviation *conflicting-bj-clss-yet* $b S \equiv$
 $3 \wedge b - \text{card } (\text{conflicting-bj-clss } S)$

abbreviation $\mu_L :: \text{nat} \Rightarrow 'st \Rightarrow \text{nat} \times \text{nat}$ **where**
 $\mu_L b S \equiv (\text{conflicting-bj-clss-yet } b S, \text{card } (\text{set-mset } (\text{clauses}_{NOT} S)))$

lemma *remove1-mset-single-add-if*:
remove1-mset $L (C + \{\#L'\# \}) = (\text{if } L = L' \text{ then } C \text{ else } \text{remove1-mset } L C + \{\#L'\# \})$
by (*auto simp: multiset-eq-iff*)

lemma *do-not-forget-before-backtrack-rule-clause-learned-clause-untouched*:
assumes *forget_{NOT}* $S T$
shows *conflicting-bj-clss* $S =$ *conflicting-bj-clss* T
using *assms* **apply** (*elim forget_{NOT}E*)
apply *rule*
apply (*subst conflicting-bj-clss-remove-clss_{NOT}'*[*of T*], *simp*)
apply (*fastforce simp: conflicting-bj-clss-def remove1-mset-single-add-if split: if-splits*)
apply *fastforce*
done

lemma *forget- μ_L -decrease*:
assumes *forget_{NOT}*: *forget_{NOT}* $S T$
shows $(\mu_L b T, \mu_L b S) \in \text{less-than} <*\text{lex*}> \text{less-than}$
proof –
have $\text{card } (\text{set-mset } (\text{clauses}_{NOT} S)) > 0$
using *forget_{NOT}* **by** (*elim forget_{NOT}E*) (*auto simp: size-mset-removeAll-mset-le-iff card-gt-0-iff*)
then have $\text{card } (\text{set-mset } (\text{clauses}_{NOT} T)) < \text{card } (\text{set-mset } (\text{clauses}_{NOT} S))$
using *forget_{NOT}* **by** (*elim forget_{NOT}E*) (*auto simp: size-mset-removeAll-mset-le-iff*)
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*:
 $A \neq \text{insert } a A \iff a \notin A$

by auto

lemma *learn- μ_L -decrease*:

assumes *learnST*: *learn S T* **and** *n-d*: *no-dup (trail S)* **and**
A: *atms-of-mm (clauses_{NOT} S) \cup atm-of ' lits-of-l (trail S) \subseteq A* **and**
fin-A: *finite A*
shows $(\mu_L (\text{card } A) \ T, \mu_L (\text{card } A) \ S) \in \text{less-than } <*\text{lex}*> \text{less-than}$

proof –

have [*simp*]: $(\text{atms-of-mm } (\text{clauses}_{NOT} \ T) \cup \text{atm-of ' lits-of-l } (\text{trail } T))$
 $= (\text{atms-of-mm } (\text{clauses}_{NOT} \ S) \cup \text{atm-of ' lits-of-l } (\text{trail } S))$
using *learnST n-d* **by** $(\text{elim } \text{learn}_{NOT} E)$ *auto*

then have $\text{card } (\text{atms-of-mm } (\text{clauses}_{NOT} \ T) \cup \text{atm-of ' lits-of-l } (\text{trail } T))$
 $= \text{card } (\text{atms-of-mm } (\text{clauses}_{NOT} \ S) \cup \text{atm-of ' lits-of-l } (\text{trail } S))$
by $(\text{auto intro!} : \text{card-mono})$

then have $3: (3::\text{nat}) \wedge \text{card } (\text{atms-of-mm } (\text{clauses}_{NOT} \ T) \cup \text{atm-of ' lits-of-l } (\text{trail } T))$
 $= 3 \wedge \text{card } (\text{atms-of-mm } (\text{clauses}_{NOT} \ S) \cup \text{atm-of ' lits-of-l } (\text{trail } S))$
by $(\text{auto intro} : \text{power-mono})$

moreover have *conflicting-bj-clss S \subseteq conflicting-bj-clss T*
using *learnST n-d* **by** $(\text{simp add} : \text{learn-conflicting-increasing})$

moreover have *conflicting-bj-clss S \neq conflicting-bj-clss T*
using *learnST*

proof $(\text{elim } \text{learn}_{NOT} E, \text{goal-cases})$

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' @ Decided K # F* **and**

C: *C = C' + {#L#}* **and**

F: *F $\models_{as} C \text{Not } C'$* **and**

C-S: *C' + {#L#} $\notin \# \text{clauses}_{NOT} S$*

by *blast*

moreover have *distinct-mset C \neg tautology C* **using** *inv* **by** *blast+*

ultimately have *C' + {#L#} \in conflicting-bj-clss T*

using *T n-d unfolding conflicting-bj-clss-def* **by** *fastforce*

moreover have *C' + {#L#} \notin 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 $\text{card } (\text{conflicting-bj-clss } T) \geq \text{card } (\text{conflicting-bj-clss } S)$

using *card-mono* **by** *blast*

moreover

have *fin'*: *finite (atms-of-mm (clauses_{NOT} T) \cup atm-of ' lits-of-l (trail T))*
by *auto*

have *1*: *atms-of-ms (conflicting-bj-clss T) \subseteq atms-of-mm (clauses_{NOT} 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*

$\subseteq \text{simple-clss } (\text{atms-of-mm } (\text{clauses}_{NOT} \ T) \cup \text{atm-of ' lits-of-l } (\text{trail } T))$

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 $\# : 3 \wedge \text{card } (\text{atms-of-mm } (\text{clauses}_{NOT} \ T) \cup \text{atm-of ' lits-of-l } (\text{trail } T))$
 $\geq \text{card } (\text{conflicting-bj-clss } T)$

```

  by (meson Nat.le-trans simple-clss-card simple-clss-finite card-mono fin')
have atms-of-mm (clausesNOT T)  $\cup$  atm-of ' lits-of-l (trail T)  $\subseteq$  A
  using learnNOTE[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 (conflicting-bj-clss S  $\neq$  conflicting-bj-clss T)
    (conflicting-bj-clss S  $\subseteq$  conflicting-bj-clss T)
    diff-less-mono2 le-less-trans not-le psubsetI)
qed

```

We have to assume the following:

- *inv S*: the invariant holds in the initial state.
- *A* is a (finite *finite A*) superset of the literals in the trail *atm-of ' lits-of-l (trail S) \subseteq atms-of-ms A* and in the clauses *atms-of-mm (clauses_{NOT} S) \subseteq atms-of-ms A*. This can be the set of all the literals in the starting set of clauses.
- *no-dup (trail S)*: no duplicate in the trail. This is invariant along the path.

definition μ_{CDCL} where

$$\mu_{CDCL} A T \equiv ((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A)) \\ - \mu_C (1 + \text{card } (\text{atms-of-ms } A)) (2 + \text{card } (\text{atms-of-ms } A)) (\text{trail-weight } T), \\ \text{conflicting-bj-clss-yet } (\text{card } (\text{atms-of-ms } A)) T, \text{card } (\text{set-mset } (\text{clauses}_{NOT} T)))$$

lemma *cdcl_{NOT}-decreasing-measure*:

```

assumes
  cdclNOT S T and
  inv: inv S and
  atm-clss: atms-of-mm (clausesNOT S)  $\subseteq$  atms-of-ms A and
  atm-lits: atm-of ' lits-of-l (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  $\mu_{CDCL}$ -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 learnNOTE) auto
  show ?case
    using learn- $\mu_L$ -decrease[OF learn n-d, of atms-of-ms A] atm-clss atm-lits fin-A n-d
    unfolding S  $\mu_{CDCL}$ -def by auto
next
  case (c-forgetNOT T) note forgetNOT = this(1)
  have trail S = trail T using forgetNOT 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-mm (clauses_{NOT} S) \subseteq atms-of-ms A \wedge atm-of ' lits-of-l (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 $\mu_C' :: 'v \text{ clause set} \Rightarrow 'st \Rightarrow \text{nat}$ **where**

$\mu_C' A T \equiv \mu_C (1 + \text{card (atms-of-ms A)}) (2 + \text{card (atms-of-ms A)}) (\text{trail-weight T})$

definition $\mu_{CDCL}' :: 'v \text{ clause set} \Rightarrow 'st \Rightarrow \text{nat}$ **where**

$\mu_{CDCL}' A T \equiv$

$((2 + \text{card (atms-of-ms A)}) \wedge (1 + \text{card (atms-of-ms A)}) - \mu_C' A T) * (1 + 3^{\text{card (atms-of-ms A)}}) * 2$
 $+ \text{conflicting-bj-clss-yet (card (atms-of-ms A)) T} * 2$
 $+ \text{card (set-mset (clauses_{NOT} T))}$

lemma *cdcl_{NOT}-decreasing-measure'*:

assumes

cdcl_{NOT} S T and

inv: inv S and

atms-clss: atms-of-mm (clauses_{NOT} S) \subseteq atms-of-ms A and

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

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

fin-A: finite A

shows $\mu_{CDCL}' A T < \mu_{CDCL}' A S$

using *assms(1)*

proof (*induction rule: cdcl_{NOT}-learn-all-induct*)

case (*dpll-bj T*)

then have $(2 + \text{card (atms-of-ms A)}) \wedge (1 + \text{card (atms-of-ms A)}) - \mu_C' A T$

$< (2 + \text{card (atms-of-ms A)}) \wedge (1 + \text{card (atms-of-ms A)}) - \mu_C' A S$

using *dpll-bj-trail-mes-decreasing-prop fin-A inv n-d atms-clss atms-trail*

unfolding μ_C' -def **by** *blast*

then have *XX*: $((2 + \text{card (atms-of-ms A)}) \wedge (1 + \text{card (atms-of-ms A)}) - \mu_C' A T) + 1$

$\leq (2 + \text{card (atms-of-ms A)}) \wedge (1 + \text{card (atms-of-ms A)}) - \mu_C' A S$

by *auto*

from *mult-le-mono1*[*OF this, of 1 + 3^{card (atms-of-ms A)}*]

have $((2 + \text{card (atms-of-ms A)}) \wedge (1 + \text{card (atms-of-ms A)}) - \mu_C' A T) * (1 + 3^{\text{card (atms-of-ms A)}}) + (1 + 3^{\text{card (atms-of-ms A)}})$

$\leq ((2 + \text{card (atms-of-ms A)}) \wedge (1 + \text{card (atms-of-ms A)}) - \mu_C' A S)$

$* (1 + 3^{\text{card (atms-of-ms A)}})$

unfolding *Nat.add-mult-distrib*

by *presburger*

moreover

have *cl-T-S*: $\text{clauses}_{NOT} T = \text{clauses}_{NOT} S$

using *dpll-bj.hyps inv dpll-bj-clauses* **by** *auto*

have *conflicting-bj-clss-yet (card (atms-of-ms A)) S* $< 1 + 3^{\text{card (atms-of-ms A)}}$

by *simp*

ultimately have $((2 + \text{card (atms-of-ms A)}) \wedge (1 + \text{card (atms-of-ms A)}) - \mu_C' A T)$


```

    * (1 + 3 ^ card (atms-of-ms A)) + conflicting-bj-clss-yet (card (atms-of-ms A)) T
  < ((2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A)) - μC' A S) * (1 + 3 ^ card (atms-of-ms
A))
  by linarith
then have ((2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A)) - μC' A T)
  * (1 + 3 ^ card (atms-of-ms A))
  + conflicting-bj-clss-yet (card (atms-of-ms A)) T
  < ((2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A)) - μC' A S)
  * (1 + 3 ^ card (atms-of-ms A))
  + conflicting-bj-clss-yet (card (atms-of-ms A)) S
  by linarith
then have ((2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A)) - μC' A T)
  * (1 + 3 ^ card (atms-of-ms A)) * 2
  + conflicting-bj-clss-yet (card (atms-of-ms A)) T * 2
  < ((2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A)) - μC' A S)
  * (1 + 3 ^ card (atms-of-ms A)) * 2
  + conflicting-bj-clss-yet (card (atms-of-ms A)) S * 2
  by linarith
then show ?case unfolding μC'DCL'-def cl-T-S by presburger
next
case (learn C F' K F C' L T) note clss-S-C = this(1) and atms-C = this(2) and dist = this(3)
  and tauto = this(4) and learn-restr = this(5) and tr-S = this(6) and C' = this(7) and
  F-C = this(8) and C-new = this(9) and T = this(10)
have insert C (conflicting-bj-clss S) ⊆ simple-clss (atms-of-ms A)
proof -
  have C ∈ simple-clss (atms-of-ms A)
  using C'
  by (metis (no-types, hide-lams) Un-subset-iff simple-clss-mono
    contra-subsetD dist distinct-mset-not-tautology-implies-in-simple-clss
    dual-order.trans atms-C atms-clss atms-trail tauto)
  moreover have conflicting-bj-clss S ⊆ simple-clss (atms-of-ms A)
  proof
    fix x :: 'v clause
    assume x ∈ conflicting-bj-clss S
    then have x ∈ # clausesNOT S ∧ distinct-mset x ∧ ¬ tautology x
    unfolding conflicting-bj-clss-def by blast
    then show x ∈ simple-clss (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
      set-rev-mp)
  qed
  ultimately show ?thesis
  by auto
qed
then have card (insert C (conflicting-bj-clss S)) ≤ 3 ^ (card (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]: card (insert C (conflicting-bj-clss S))
  = Suc (card ((conflicting-bj-clss S)))
  by (metis (no-types) C' C-new card-insert-if conflicting-bj-clss-incl-clauses contra-subsetD
    finite-conflicting-bj-clss)
moreover have [simp]: conflicting-bj-clss (add-clNOT C S) = conflicting-bj-clss S ∪ {C}
  using dist tauto F-C by (subst conflicting-bj-clss-add-clNOT[OF n-d]) (force simp: C' tr-S n-d)
ultimately have [simp]: conflicting-bj-clss-yet (card (atms-of-ms A)) S
  = Suc (conflicting-bj-clss-yet (card (atms-of-ms A)) (add-clNOT C S))
  by simp

```

have 1: $\text{clauses}_{NOT} T = \text{clauses}_{NOT} (\text{add-cl}_{NOT} C S)$ **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** $\text{conflicting-bj-clss-def}$ **by** *auto*
have 3: $\mu_C' A T = \mu_C' A (\text{add-cl}_{NOT} C S)$
using T **unfolding** $\mu_C'\text{-def}$ **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 $n\text{-d}$ **unfolding** $\mu_C'\text{-def}$ **by** *auto*
moreover
have $\text{conflicting-bj-clss-yet} (\text{card} (\text{atms-of-ms } A)) (\text{add-cl}_{NOT} C S)$
 $* 2$
 $+ \text{card} (\text{set-mset} (\text{clauses}_{NOT} (\text{add-cl}_{NOT} C S)))$
 $< \text{conflicting-bj-clss-yet} (\text{card} (\text{atms-of-ms } A)) S * 2$
 $+ \text{card} (\text{set-mset} (\text{clauses}_{NOT} S))$
by (*simp add: C' C-new n-d*)
ultimately show $?case$ **unfolding** $\mu_{CDCL}'\text{-def 1 2 3}$ **by** *presburger*
next
case ($\text{forget}_{NOT} C T$) **note** $T = \text{this}(4)$
have [*simp*]: $\mu_C' A (\text{remove-cl}_{NOT} C S) = \mu_C' A S$
unfolding $\mu_C'\text{-def}$ **by** *auto*
have $\text{forget}_{NOT} S T$
apply (*rule forget_{NOT}.intros*) **using** forget_{NOT} **by** *auto*
then have $\text{conflicting-bj-clss } T = \text{conflicting-bj-clss } S$
using *do-not-forget-before-backtrack-rule-clause-learned-clause-untouched* **by** *blast*
moreover have $\text{card} (\text{set-mset} (\text{clauses}_{NOT} T)) < \text{card} (\text{set-mset} (\text{clauses}_{NOT} S))$
by (*metis T card-Diff1-less clauses-remove-cl_{NOT} finite-set-mset forget_{NOT}.hyps(2)*
 $\text{order-refl set-mset-minus-replicate-mset}(1) \text{ state-eq}_{NOT}\text{-clauses}$)
ultimately show $?case$ **unfolding** $\mu_{CDCL}'\text{-def}$
using $T \mu_C' A (\text{remove-cl}_{NOT} C S) = \mu_C' A S$ **by** (*metis (no-types) add-le-cancel-left*
 $\mu_C'\text{-def not-le state-eq}_{NOT}\text{-trail}$)
qed

lemma $\text{cdcl}_{NOT}\text{-clauses-bound}$:

assumes
 $\text{cdcl}_{NOT} S T$ **and**
 $\text{inv } S$ **and**
 $\text{atms-of-mm} (\text{clauses}_{NOT} S) \subseteq A$ **and**
 $\text{atm-of } (\text{lits-of-l } (\text{trail } S)) \subseteq A$ **and**
 $n\text{-d: no-dup } (\text{trail } S)$ **and**
 $\text{fin-}A[\text{simp}]: \text{finite } A$
shows $\text{set-mset} (\text{clauses}_{NOT} T) \subseteq \text{set-mset} (\text{clauses}_{NOT} S) \cup \text{simple-clss } A$
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** $\text{clauses-remove-cl}_{NOT}$ **unfolding** $\text{state-eq}_{NOT}\text{-def}$ **by** *auto*
next
case ($\text{learn } C F K d F' C' L$) **note** $\text{atms-}C = \text{this}(2)$ **and** $\text{dist} = \text{this}(3)$ **and** $\text{tauto} = \text{this}(4)$ **and**
 $T = \text{this}(10)$ **and** $\text{atms-clss-}S = \text{this}(12)$ **and** $\text{atms-trail-}S = \text{this}(13)$
have $\text{atms-of } C \subseteq A$
using $\text{atms-}C \text{ atms-clss-}S \text{ atms-trail-}S$ **by** *fast*

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-mm (clauses_{NOT} S) \subseteq A **and**
atm-of '(lits-of-l (trail S)) \subseteq A **and**
n-d: no-dup (trail S) **and**
finite: finite A
shows *set-mset (clauses_{NOT} T) \subseteq set-mset (clauses_{NOT} 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 = this(1)* **and** *cdcl_{NOT} = 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 *inv T*
using *rtrancpl-cdcl_{NOT}-inv st inv* **by** *blast*
moreover have *atms-of-mm (clauses_{NOT} T) \subseteq A* **and** *atm-of '(lits-of-l (trail T)) \subseteq A*
using *rtrancpl-cdcl_{NOT}-trail-clauses-bound[OF st] inv atms-clss-S atms-trail-S n-d* **by** *auto*
moreover have *no-dup (trail T)*
using *rtrancpl-cdcl_{NOT}-no-dup[OF st (inv S) n-d]* **by** *simp*
ultimately have *set-mset (clauses_{NOT} U) \subseteq set-mset (clauses_{NOT} T) \cup simple-clss A*
using *cdcl_{NOT} finite n-d* **by** (*auto simp: cdcl_{NOT}-clauses-bound*)
then show ?*case* **using** *IH* **by** *auto*
qed

lemma *rtrancpl-cdcl_{NOT}-card-clauses-bound*:

assumes
*cdcl_{NOT}** S T* **and**
inv S **and**
atms-of-mm (clauses_{NOT} S) \subseteq A **and**
atm-of '(lits-of-l (trail S)) \subseteq A **and**
n-d: no-dup (trail S) **and**
finite: finite A
shows *card (set-mset (clauses_{NOT} T)) \leq card (set-mset (clauses_{NOT} S)) + 3 \wedge (card A)*
using *rtrancpl-cdcl_{NOT}-clauses-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 *rtrancpl-cdcl_{NOT}-card-clauses-bound'*:

assumes
*cdcl_{NOT}** S T* **and**
inv S **and**
atms-of-mm (clauses_{NOT} S) \subseteq A **and**
atm-of '(lits-of-l (trail S)) \subseteq A **and**
n-d: no-dup (trail S) **and**
finite: finite A
shows *card {C | C. C \in # clauses_{NOT} T \wedge (tautology C \vee \neg distinct-mset C)}*

$\leq \text{card } \{C \mid C. C \in \# \text{ clauses}_{NOT} S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\} + 3 \wedge (\text{card } A)$
 (is card ?T ≤ card ?S + -)
 using rtrancpl-cdcl_{NOT}-clauses-bound[OF assms] finite
proof –
 have ?T ⊆ ?S ∪ simple-clss A
 using rtrancpl-cdcl_{NOT}-clauses-bound[OF assms] by force
 then have card ?T ≤ card (?S ∪ 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

lemma rtrancpl-cdcl_{NOT}-card-simple-clauses-bound:

assumes
 cdcl_{NOT}** S T and
 inv S and
 NA: atms-of-mm (clauses_{NOT} S) ⊆ A and
 MA: atm-of '(lits-of-l (trail S)) ⊆ A and
 n-d: no-dup (trail S) and
 finite: finite A
shows card (set-mset (clauses_{NOT} T))
 $\leq \text{card } \{C. C \in \# \text{ clauses}_{NOT} S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\} + 3 \wedge (\text{card } A)$
 (is card ?T ≤ card ?S + -)
 using rtrancpl-cdcl_{NOT}-clauses-bound[OF assms] finite
proof –
 have $\bigwedge x. x \in \# \text{ clauses}_{NOT} T \implies \neg \text{tautology } x \implies \text{distinct-mset } x \implies x \in \text{simple-clss } A$
 using rtrancpl-cdcl_{NOT}-clauses-bound[OF assms] by (metis (no-types, hide-lams) Un-iff NA
 atms-of-atms-of-ms-mono simple-clss-mono contra-subsetD subset-trans
 distinct-mset-not-tautology-implies-in-simple-clss)
 then have set-mset (clauses_{NOT} T) ⊆ ?S ∪ simple-clss A
 using rtrancpl-cdcl_{NOT}-clauses-bound[OF assms] by auto
 then have card(set-mset (clauses_{NOT} T)) ≤ card (?S ∪ 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 $\mu_{CDCL}'\text{-bound} :: 'v \text{ clause set} \Rightarrow 'st \Rightarrow \text{nat}$ **where**

$\mu_{CDCL}'\text{-bound } A \ S =$
 $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))) * (1 + 3 \wedge \text{card } (\text{atms-of-ms } A)) * 2$
 $+ 2 * 3 \wedge (\text{card } (\text{atms-of-ms } A))$
 $+ \text{card } \{C. C \in \# \text{ clauses}_{NOT} S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\} + 3 \wedge (\text{card } (\text{atms-of-ms } A))$

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 rtrancpl-cdcl_{NOT}- $\mu_{CDCL}'\text{-bound-reduce-trail-to}_{NOT}$:

assumes
 cdcl_{NOT}** S T and
 inv S and
 atms-of-mm (clauses_{NOT} S) ⊆ atms-of-ms A and
 atm-of '(lits-of-l (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 *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 $\text{card } (\text{set-mset } (\text{clauses}_{NOT} U))$
 $\leq \text{card } \{C. C \in \# \text{ clauses}_{NOT} S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\} + 3 \wedge \text{card } (\text{atms-of-ms } A)$
 using *rtranclp-cdcl_{NOT}-card-simple-clauses-bound*[*OF assms(1-6)*] *U* by *auto*
ultimately show *?thesis*
 unfolding $\mu_{CDCL}'\text{-def}$ $\mu_{CDCL}'\text{-bound-def}$ by *linarith*
qed

lemma *rtranclp-cdcl_{NOT}- μ_{CDCL}' -bound*:

assumes
 $\text{cdcl}_{NOT}^{**} S T$ **and**
 $\text{inv } S$ **and**
 $\text{atms-of-mm } (\text{clauses}_{NOT} S) \subseteq \text{atms-of-ms } A$ **and**
 $\text{atm-of } (\text{lits-of-l } (\text{trail } S)) \subseteq \text{atms-of-ms } A$ **and**
 $n\text{-d: no-dup } (\text{trail } S)$ **and**
 $\text{finite: finite } (\text{atms-of-ms } A)$
 shows $\mu_{CDCL}' A T \leq \mu_{CDCL}'\text{-bound } A S$
proof –
 have $\mu_{CDCL}' A (\text{reduce-trail-to}_{NOT} (\text{trail } T) T) = \mu_{CDCL}' A T$
 unfolding $\mu_{CDCL}'\text{-def}$ $\mu_C'\text{-def}$ *conflicting-bj-clss-def* by *auto*
 then show *?thesis* using *rtranclp-cdcl_{NOT}- μ_{CDCL}' -bound-reduce-trail-to_{NOT}*[*OF assms, of - trail T*]
 $\text{state-eq}_{NOT}\text{-ref}$ by *fastforce*
qed

lemma *rtranclp- μ_{CDCL}' -bound-decreasing*:

assumes
 $\text{cdcl}_{NOT}^{**} S T$ **and**
 $\text{inv } S$ **and**
 $\text{atms-of-mm } (\text{clauses}_{NOT} S) \subseteq \text{atms-of-ms } A$ **and**
 $\text{atm-of } (\text{lits-of-l } (\text{trail } S)) \subseteq \text{atms-of-ms } A$ **and**
 $n\text{-d: no-dup } (\text{trail } S)$ **and**
 $\text{finite[simp]: finite } (\text{atms-of-ms } A)$
 shows $\mu_{CDCL}'\text{-bound } A T \leq \mu_{CDCL}'\text{-bound } A S$
proof –
 have $\{C. C \in \# \text{ clauses}_{NOT} T \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\}$
 $\subseteq \{C. C \in \# \text{ clauses}_{NOT} S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)\}$ (**is** $?T \subseteq ?S$)
proof (*rule Set.subsetI*)
 fix *C* **assume** $C \in ?T$
 then have *C-T*: $C \in \# \text{ clauses}_{NOT} T$ **and** *t-d*: $\text{tautology } C \vee \neg \text{distinct-mset } C$
 by *auto*
 then have $C \notin \text{simple-clss } (\text{atms-of-ms } A)$
 by (*auto dest: simple-clssE*)
 then show $C \in ?S$
 using *C-T* *rtranclp-cdcl_{NOT}-clauses-bound*[*OF assms*] *t-d* by *force*
qed

```

then have card { $C. C \in \# \text{ clauses}_{NOT} T \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)$ }  $\leq$ 
  card { $C. C \in \# \text{ clauses}_{NOT} S \wedge (\text{tautology } C \vee \neg \text{distinct-mset } C)$ }
by (simp add: card-mono)
then show ?thesis
  unfolding  $\mu_{CDCL}$ '-bound-def by auto
qed

end — end of conflict-driven-clause-learning-learning-before-backjump-only-distinct-learnt

```

5.2.5 CDCL with restarts

Definition

```

locale restart-ops =
  fixes
    cdclNOT :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool and
    restart :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool
  begin
inductive cdclNOT-raw-restart :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
  cdclNOT  $S\ T \Longrightarrow$  cdclNOT-raw-restart  $S\ T$  |
  restart  $S\ T \Longrightarrow$  cdclNOT-raw-restart  $S\ T$ 

end

locale conflict-driven-clause-learning-with-restarts =
  conflict-driven-clause-learning trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT
  inv backjump-conds propagate-conds learn-cond forget-cond
  for
    trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
    clausesNOT :: 'st  $\Rightarrow$  'v clauses and
    prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
    tl-trail :: 'st  $\Rightarrow$  'st and
    add-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
    remove-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
    inv :: 'st  $\Rightarrow$  bool and
    backjump-conds :: 'v clause  $\Rightarrow$  'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool and
    propagate-conds :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  bool and
    learn-cond forget-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool
  begin

lemma cdclNOT-iff-cdclNOT-raw-restart-no-restarts:
  cdclNOT  $S\ T \longleftrightarrow$  restart-ops.cdclNOT-raw-restart cdclNOT ( $\lambda -.$  False)  $S\ T$ 
  (is ? $C\ S\ T \longleftrightarrow$  ? $R\ S\ T$ )
proof
  fix  $S\ T$ 
  assume ? $C\ S\ T$ 
  then show ? $R\ S\ T$  by (simp add: restart-ops.cdclNOT-raw-restart.intros(1))
next
  fix  $S\ T$ 
  assume ? $R\ S\ T$ 
  then show ? $C\ S\ T$ 
    apply (cases rule: restart-ops.cdclNOT-raw-restart.cases)
    using ⟨? $R\ S\ T$ ⟩ by fast+
qed

lemma cdclNOT-cdclNOT-raw-restart:

```

```

cdclNOT S T  $\implies$  restart-ops.cdclNOT-raw-restart cdclNOT restart S T
by (simp add: restart-ops.cdclNOT-raw-restart.intros(1))
end

```

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 cdclNOT-increasing-restarts-ops =
  restart-ops cdclNOT restart for
    restart :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool and
    cdclNOT :: '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
  cdclNOT-inv :: 'st  $\Rightarrow$  bool and
   $\mu$ -bound :: 'bound  $\Rightarrow$  'st  $\Rightarrow$  nat
assumes
  f: unbounded f and
  f-ge-1:  $\bigwedge n. n \geq 1 \implies f\ n \neq 0$  and
  bound-inv:  $\bigwedge A\ S\ T. \text{cdcl}_{NOT-inv}\ S \implies \text{bound-inv}\ A\ S \implies \text{cdcl}_{NOT}\ S\ T \implies \text{bound-inv}\ A\ T$  and
  cdclNOT-measure:  $\bigwedge A\ S\ T. \text{cdcl}_{NOT-inv}\ S \implies \text{bound-inv}\ A\ S \implies \text{cdcl}_{NOT}\ S\ T \implies \mu\ A\ T < \mu$ 
  A S and
  measure-bound2:  $\bigwedge A\ T\ U. \text{cdcl}_{NOT-inv}\ T \implies \text{bound-inv}\ A\ T \implies \text{cdcl}_{NOT}^{**}\ T\ U$ 
     $\implies \mu\ A\ U \leq \mu\text{-bound}\ A\ T$  and
  measure-bound4:  $\bigwedge A\ T\ U. \text{cdcl}_{NOT-inv}\ T \implies \text{bound-inv}\ A\ T \implies \text{cdcl}_{NOT}^{**}\ T\ U$ 
     $\implies \mu\text{-bound}\ A\ U \leq \mu\text{-bound}\ A\ T$  and
  cdclNOT-restart-inv:  $\bigwedge A\ U\ V. \text{cdcl}_{NOT-inv}\ U \implies \text{restart}\ U\ V \implies \text{bound-inv}\ A\ U \implies \text{bound-inv}$ 
  A V
and
  exists-bound:  $\bigwedge R\ S. \text{cdcl}_{NOT-inv}\ R \implies \text{restart}\ R\ S \implies \exists A. \text{bound-inv}\ A\ S$  and
  cdclNOT-inv:  $\bigwedge S\ T. \text{cdcl}_{NOT-inv}\ S \implies \text{cdcl}_{NOT}\ S\ T \implies \text{cdcl}_{NOT-inv}\ T$  and
  cdclNOT-inv-restart:  $\bigwedge S\ T. \text{cdcl}_{NOT-inv}\ S \implies \text{restart}\ S\ T \implies \text{cdcl}_{NOT-inv}\ T$ 
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:  $cdcl_{NOT-inv}$ )

lemma  $rtrancp-cdcl_{NOT-bound-inv}$ :
assumes
   $cdcl_{NOT}^{**}$   $S$   $T$  and
  bound-inv  $A$   $S$  and
   $cdcl_{NOT-inv}$   $S$ 
shows bound-inv  $A$   $T$ 
using assms by induction (auto intro:bound-inv  $rtrancp-cdcl_{NOT}$ - $cdcl_{NOT-inv}$ )

lemma  $cdcl_{NOT-comp-n-le}$ :
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  $cdcl_{NOT-measure}$  by auto
  next
    case ( $Suc\ n$ ) note  $IH = this(1)[OF - this(3)\ this(4)]$  and  $S-T = this(2)$  and  $b-inv = this(3)$  and
     $c-inv = this(4)$ 
    obtain  $U :: 'st$  where  $S-U: (cdcl_{NOT} \sim (Suc\ n))\ S\ U$  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  $wf-cdcl_{NOT}$ :
   $wf\ \{(T, S).\ cdcl_{NOT}\ S\ T \wedge cdcl_{NOT-inv}\ S \wedge bound-inv\ A\ S\}$  (is  $wf\ ?A$ )
apply (rule  $wfP-if-measure2[of\ -\ -\ \mu\ A]$ )
using  $cdcl_{NOT-comp-n-le}[of\ 0\ -\ A]$  by auto

```


lemma *rtrancpl-cdcl_{NOT}-measure*:
assumes
 $cdcl_{NOT}^{**} S T$ **and**
 $bound-inv A S$ **and**
 $cdcl_{NOT-inv} S$
shows $\mu A T \leq \mu A S$
using *assms*
proof (*induction rule: rtrancpl-induct*)
case *base*
then show *?case* **by** *auto*
next
case (*step* $T U$) **note** $IH = this(3)[OF\ this(4)\ this(5)]$ **and** $st = this(1)$ **and** $cdcl_{NOT} = this(2)$
and
 $b-inv = this(4)$ **and** $c-inv = this(5)$
have $bound-inv A T$
by (*meson* $cdcl_{NOT-bound-inv}\ rtrancpl-imp-relpowp\ st\ step.premis$)
moreover have $cdcl_{NOT-inv} T$
using $c-inv\ rtrancpl-cdcl_{NOT-cdcl_{NOT-inv}\ st}$ **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 $\neg(cdcl_{NOT} \sim^m) S T$
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: $(cdcl_{NOT} \sim^m) S T \implies m \geq f\ n \implies restart\ T\ U$
 $\implies cdcl_{NOT-restart}\ (S, n)\ (U, Suc\ n) \mid$
restart-full: $full1\ cdcl_{NOT}\ S\ T \implies cdcl_{NOT-restart}\ (S, n)\ (T, Suc\ n)$

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*:
 $cdcl_{NOT-restart}\ S\ T \implies cdcl_{NOT-raw-restart}^{**}\ (fst\ S)\ (fst\ T)$
proof (*induction rule: cdcl_{NOT}-restart.induct*)
case (*restart-step* $m\ S\ T\ n\ U$)
then have $cdcl_{NOT}^{**}\ S\ T$ **by** (*meson* $relpowp-imp-rtrancpl$)
then have $cdcl_{NOT-raw-restart}^{**}\ S\ T$ **using** $cdcl_{NOT-raw-restart}.intros(1)$
 $rtrancpl-mono[of\ cdcl_{NOT}\ cdcl_{NOT-raw-restart}]$ **by** *blast*
moreover have $cdcl_{NOT-raw-restart}\ T\ U$
using $\langle restart\ T\ U \rangle\ cdcl_{NOT-raw-restart}.intros(2)$ **by** *blast*
ultimately show *?case* **by** *auto*
next
case (*restart-full* $S\ T$)
then have $cdcl_{NOT}^{**}\ S\ T$ **unfolding** *full1-def* **by** *auto*
then show *?case* **using** $cdcl_{NOT-raw-restart}.intros(1)$
 $rtrancpl-mono[of\ cdcl_{NOT}\ cdcl_{NOT-raw-restart}]$ **by** *auto*
qed

lemma *cdcl_{NOT}-with-restart-bound-inv*:

assumes

cdcl_{NOT}-restart *S T* **and**

bound-inv *A (fst S)* **and**

cdcl_{NOT}-inv *(fst S)*

shows *bound-inv* *A (fst T)*

using *assms* **apply** (*induction rule: cdcl_{NOT}-restart.induct*)

prefer 2 **apply** (*metis rtranclp-unfold fstI full1-def rtranclp-cdcl_{NOT}-bound-inv*)

by (*metis cdcl_{NOT}-bound-inv cdcl_{NOT}-cdcl_{NOT}-inv cdcl_{NOT}-restart-inv fst-conv*)

lemma *cdcl_{NOT}-with-restart-cdcl_{NOT}-inv*:

assumes

cdcl_{NOT}-restart *S T* **and**

cdcl_{NOT}-inv *(fst S)*

shows *cdcl_{NOT}-inv* *(fst T)*

using *assms* **apply** *induction*

apply (*metis cdcl_{NOT}-cdcl_{NOT}-inv cdcl_{NOT}-inv-restart fst-conv*)

apply (*metis fstI full-def full-unfold rtranclp-cdcl_{NOT}-cdcl_{NOT}-inv*)

done

lemma *rtranclp-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv*:

assumes

*cdcl_{NOT}-restart*** *S T* **and**

cdcl_{NOT}-inv *(fst S)*

shows *cdcl_{NOT}-inv* *(fst T)*

using *assms* **by** *induction (auto intro: cdcl_{NOT}-with-restart-cdcl_{NOT}-inv)*

lemma *rtranclp-cdcl_{NOT}-with-restart-bound-inv*:

assumes

*cdcl_{NOT}-restart*** *S T* **and**

cdcl_{NOT}-inv *(fst S)* **and**

bound-inv *A (fst S)*

shows *bound-inv* *A (fst T)*

using *assms* **apply** *induction*

apply (*simp add: cdcl_{NOT}-cdcl_{NOT}-inv cdcl_{NOT}-with-restart-bound-inv*)

using *cdcl_{NOT}-with-restart-bound-inv rtranclp-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv* **by** *blast*

lemma *cdcl_{NOT}-with-restart-increasing-number*:

cdcl_{NOT}-restart *S T* $\implies \text{snd } T = 1 + \text{snd } S$

by (*induction rule: cdcl_{NOT}-restart.induct*) *auto*

end

locale *cdcl_{NOT}-increasing-restarts* =

cdcl_{NOT}-increasing-restarts-ops *restart cdcl_{NOT} f bound-inv μ cdcl_{NOT}-inv μ -bound +*

dpll-state trail clauses_{NOT} prepend-trail tl-trail add-cl_s_{NOT} remove-cl_s_{NOT}

for

trail :: '*st* \Rightarrow ('*v*, *unit*) *ann-lits* **and**

clauses_{NOT} :: '*st* \Rightarrow '*v* *clauses* **and**

prepend-trail :: ('*v*, *unit*) *ann-lit* \Rightarrow '*st* \Rightarrow '*st* **and**

tl-trail :: '*st* \Rightarrow '*st* **and**

add-cl_s_{NOT} :: '*v* *clause* \Rightarrow '*st* \Rightarrow '*st* **and**

remove-cl_s_{NOT} :: '*v* *clause* \Rightarrow '*st* \Rightarrow '*st* **and**

f :: *nat* \Rightarrow *nat* **and**

restart :: '*st* \Rightarrow '*st* \Rightarrow *bool* **and**

bound-inv :: '*bound* \Rightarrow '*st* \Rightarrow *bool* **and**

```

μ :: 'bound ⇒ 'st ⇒ nat and
cdclNOT :: 'st ⇒ 'st ⇒ bool and
cdclNOT-inv :: 'st ⇒ bool and
μ-bound :: 'bound ⇒ 'st ⇒ nat +
assumes
  measure-bound:  $\bigwedge A\ T\ V\ n. \text{cdcl}_{NOT}\text{-inv } T \implies \text{bound-inv } A\ T$ 
     $\implies \text{cdcl}_{NOT}\text{-restart } (T, n) (V, \text{Suc } n) \implies \mu\ A\ V \leq \mu\text{-bound } A\ T$  and
  cdclNOT-raw-restart-μ-bound:
    cdclNOT-restart (T, a) (V, b)  $\implies \text{cdcl}_{NOT}\text{-inv } T \implies \text{bound-inv } A\ T$ 
     $\implies \mu\text{-bound } A\ V \leq \mu\text{-bound } A\ T$ 
begin

lemma rtrancp-cdclNOT-raw-restart-μ-bound:
  cdclNOT-restart** (T, a) (V, b)  $\implies \text{cdcl}_{NOT}\text{-inv } T \implies \text{bound-inv } A\ T$ 
   $\implies \mu\text{-bound } A\ V \leq \mu\text{-bound } A\ T$ 
  apply (induction rule: rtrancp-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)  $\implies \text{cdcl}_{NOT}\text{-inv } T \implies \text{bound-inv } A\ T$ 
   $\implies \mu\ A\ V \leq \mu\text{-bound } A\ T$ 
  apply (cases rule: 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)  $\implies \text{cdcl}_{NOT}\text{-inv } T \implies \text{bound-inv } A\ T$ 
   $\implies \mu\ A\ V \leq \mu\text{-bound } A\ T$ 
  apply (induction rule: 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:  $\bigwedge i. \text{cdcl}_{NOT}\text{-restart } (g\ i) (g\ (\text{Suc } i))$  and
    cdclNOT-inv-g:  $\bigwedge i. \text{cdcl}_{NOT}\text{-inv } (\text{fst } (g\ i))$ 
  unfolding wf-iff-no-infinite-down-chain by fast

  have snd-g:  $\bigwedge i. \text{snd } (g\ i) = i + \text{snd } (g\ 0)$ 
  apply (induct-tac i)
  apply simp
  by (metis Suc-eq-plus1-left add commute add.left-commute
      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 le-iff-add)

```

```

{ fix i
  have H:  $\bigwedge T \text{ Ta } m. (\text{cdcl}_{NOT} \rightsquigarrow m) T \text{ Ta} \implies \text{no-step cdcl}_{NOT} T \implies m = 0$ 
    apply (case-tac m) by simp (meson relpowp-E2)
  have  $\exists T m. (\text{cdcl}_{NOT} \rightsquigarrow m) (\text{fst } (g \ i)) T \wedge m \geq f (\text{snd } (g \ i))$ 
    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: tranclpD)
    using H Suc-leI leD by blast
} note H = this
obtain A where bound-inv A (fst (g 1))
  using g[of 0] cdclNOT-inv-g[of 0] apply (cases rule: cdclNOT-restart.cases)
  apply (metis One-nat-def cdclNOT-inv exists-bound fst-conv relpowp-imp-rtranclp
    rtranclp-induct)
  using H[of 1] unfolding full1-def by (metis One-nat-def Suc-eq-plus1 diff-is-0-eq' diff-zero
    f-ge-1 fst-conv le-add2 relpowp-E2 snd-conv)
let ?j =  $\mu$ -bound A (fst (g 1)) + 1
obtain j where
  j:  $f (\text{snd } (g \ j)) > ?j$  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 <j> 1> by (simp add: cdclNOT-restart)
have  $\mu \ A \ (\text{fst } (g \ j)) \leq \mu\text{-bound } A \ (\text{fst } (g \ 1))$ 
  apply (rule rtranclp-cdclNOT-raw-restart-measure-bound)
  using <cdclNOT-restart** (fst (g 1), snd (g 1)) (fst (g j), snd (g j))> apply blast
  apply (simp add: cdclNOT-inv-g)
  using <bound-inv A (fst (g 1))> apply simp
done
then have  $\mu \ A \ (\text{fst } (g \ j)) \leq ?j$ 
  by auto
have inv: bound-inv A (fst (g j))
  using <bound-inv A (fst (g 1))> <cdclNOT-inv (fst (g (Suc 0)))>
  <cdclNOT-restart** (fst (g 1), snd (g 1)) (fst (g j), snd (g j))>
  rtranclp-cdclNOT-with-restart-bound-inv by auto
obtain T m where
  cdclNOT-m:  $(\text{cdcl}_{NOT} \rightsquigarrow m) (\text{fst } (g \ j)) T$  and
  f-m:  $f (\text{snd } (g \ j)) \leq m$ 
  using H[of j] by blast
have ?j < m
  using f-m j Nat.le-trans by linarith

then show False
  using < $\mu \ A \ (\text{fst } (g \ j)) \leq \mu\text{-bound } A \ (\text{fst } (g \ 1))$ >
  cdclNOT-comp-bounded[OF inv cdclNOT-inv-g, of ] cdclNOT-inv-g cdclNOT-m
  <?j < m> by auto
qed

```

lemma *cdcl_{NOT}-restart-steps-bigger-than-bound*:
assumes
cdcl_{NOT}-restart S T **and**
bound-inv A (*fst* S) **and**
cdcl_{NOT}-inv (*fst* S) **and**
 f (*snd* S) $>$ μ -*bound* A (*fst* S)
shows *full1 cdcl_{NOT}* (*fst* S) (*fst* T)
using *assms*
proof (*induction rule: cdcl_{NOT}-restart.induct*)
case *restart-full*
then show ?*case* **by** *auto*
next
case (*restart-step* m S T n U) **note** $st = \text{this}(1)$ **and** $f = \text{this}(2)$ **and** $\text{bound-inv} = \text{this}(4)$ **and**
 $\text{cdcl}_{NOT}\text{-inv} = \text{this}(5)$ **and** $\mu = \text{this}(6)$
then obtain m' **where** $m: m = \text{Suc } m'$ **by** (*cases* m) *auto*
have μ A $S - m' = 0$
using f *bound-inv* *cdcl_{NOT}-inv* μ m *rtrancp-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 *rtrancp-cdcl_{NOT}-with-inv-inv-rtrancp-cdcl_{NOT}*:
assumes
inv: cdcl_{NOT}-inv S **and**
binv: bound-inv A S
shows $(\lambda S T. \text{cdcl}_{NOT} S T \wedge \text{cdcl}_{NOT}\text{-inv } S \wedge \text{bound-inv } A S)^{**} S T \longleftrightarrow \text{cdcl}_{NOT}^{**} S T$
(is ? $A^{**} S T \longleftrightarrow ?B^{**} S T$ **)**
apply (*rule iffI*)
using *rtrancp-mono*[*of* ? A ? B] **apply** *blast*
apply (*induction rule: rtrancp-induct*)
using *inv binv apply simp*
by (*metis (mono-tags, lifting) binv inv rtrancp.simps rtrancp-cdcl_{NOT}-bound-inv*
rtrancp-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** $T: \text{cdcl}_{NOT} (\text{fst } S) T$
by *blast*
then obtain U **where** $U: \text{full } (\lambda S T. \text{cdcl}_{NOT} S T \wedge \text{cdcl}_{NOT}\text{-inv } S \wedge \text{bound-inv } A S) T U$
using *wf-exists-normal-form-full*[*OF* *wf-cdcl_{NOT}*, *of* A T] **by** *auto*
moreover have *inv-T: cdcl_{NOT}-inv* T
using $\langle \text{cdcl}_{NOT} (\text{fst } S) T \rangle \text{cdcl}_{NOT}\text{-inv } \text{inv}$ **by** *blast*
moreover have *b-inv-T: bound-inv* A T
using $\langle \text{cdcl}_{NOT} (\text{fst } S) T \rangle \text{binv bound-inv } \text{inv}$ **by** *blast*
ultimately have *full cdcl_{NOT}* T U
using *rtrancp-cdcl_{NOT}-with-inv-inv-rtrancp-cdcl_{NOT}* *rtrancp-cdcl_{NOT}-bound-inv*
rtrancp-cdcl_{NOT}-cdcl_{NOT}-inv **unfolding** *full-def* **by** *blast*
then have *full1 cdcl_{NOT}* (*fst* S) U
using T *full-full1* **by** *metis*

```

    then show False by (metis n-s prod.collapse restart-full)
qed

end

```

5.2.6 Merging backjump and learning

```

locale cdclNOT-merge-bj-learn-ops =
  decide-ops trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT +
  forget-ops trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT forget-cond +
  propagate-ops trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT propagate-conds
for
  trail :: 'st ⇒ ('v, unit) ann-lits and
  clausesNOT :: 'st ⇒ 'v clauses and
  prepend-trail :: ('v, unit) ann-lit ⇒ 'st ⇒ 'st and
  tl-trail :: 'st ⇒ 'st and
  add-clNOT :: 'v clause ⇒ 'st ⇒ 'st and
  remove-clNOT :: 'v clause ⇒ 'st ⇒ 'st and
  propagate-conds :: ('v, unit) ann-lit ⇒ 'st ⇒ bool and
  forget-cond :: 'v clause ⇒ 'st ⇒ bool +
fixes backjump-l-cond :: 'v clause ⇒ 'v clause ⇒ 'v literal ⇒ 'st ⇒ 'st ⇒ bool
begin

```

We have a new backjump that combines the backjumping on the trail and the learning of the used clause (called C'' below)

```

inductive backjump-l where
backjump-l: trail S = F' @ Decided K # F
  ⇒ no-dup (trail S)
  ⇒ T ~ prepend-trail (Propagated L ()) (reduce-trail-toNOT F (add-clNOT C'' S))
  ⇒ C ∈ # clausesNOT S
  ⇒ trail S ⊨as CNot C
  ⇒ undefined-lit F L
  ⇒ atm-of L ∈ atms-of-mm (clausesNOT S) ∪ atm-of ' (lits-of-l (trail S))
  ⇒ clausesNOT S ⊨pm C' + {#L#}
  ⇒ C'' = C' + {#L#}
  ⇒ F ⊨as CNot C'
  ⇒ backjump-l-cond C C' L S T
  ⇒ backjump-l S T

```

Avoid (meaningless) simplification in the theorem generated by *inductive-cases*:

```

declare reduce-trail-toNOT-length-ne[simp del] Set.Un-iff[simp del] Set.insert-iff[simp del]
inductive-cases backjump-lE: backjump-l S T
thm backjump-lE
declare reduce-trail-toNOT-length-ne[simp] Set.Un-iff[simp] Set.insert-iff[simp]

```

```

inductive cdclNOT-merged-bj-learn :: 'st ⇒ 'st ⇒ bool for S :: 'st where
cdclNOT-merged-bj-learn-decideNOT: decideNOT S S' ⇒ cdclNOT-merged-bj-learn S S' |
cdclNOT-merged-bj-learn-propagateNOT: propagateNOT S S' ⇒ cdclNOT-merged-bj-learn S S' |
cdclNOT-merged-bj-learn-backjump-l: backjump-l S S' ⇒ cdclNOT-merged-bj-learn S S' |
cdclNOT-merged-bj-learn-forgetNOT: forgetNOT S S' ⇒ cdclNOT-merged-bj-learn S S'

```

```

lemma cdclNOT-merged-bj-learn-no-dup-inv:
  cdclNOT-merged-bj-learn S T ⇒ no-dup (trail S) ⇒ 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 clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT
  propagate-conds forget-cond
   $\lambda C\ C'\ L'\ S\ T.$  backjump-l-cond  $C\ C'\ L'\ S\ T$ 
   $\wedge$  distinct-mset  $(C' + \{\#L'\#\}) \wedge \neg$ tautology  $(C' + \{\#L'\#\})$ 
for
  trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
  clausesNOT :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  remove-clNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  propagate-conds :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  bool and
  forget-cond :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  bool and
  backjump-l-cond :: 'v clause  $\Rightarrow$  'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool +
fixes
  inv :: 'st  $\Rightarrow$  bool
assumes
  bj-merge-can-jump:
   $\bigwedge S\ C\ F'\ K\ F\ L.$ 
  inv S
   $\Rightarrow$  trail S = F' @ Decided K # F
   $\Rightarrow$  C  $\in$  # clausesNOT S
   $\Rightarrow$  trail S  $\models_{as}$  CNot C
   $\Rightarrow$  undefined-lit F L
   $\Rightarrow$  atm-of L  $\in$  atms-of-mm (clausesNOT S)  $\cup$  atm-of ' (lits-of-l (F' @ Decided K # F))
   $\Rightarrow$  clausesNOT S  $\models_{pm}$  C' + {#L'#}
   $\Rightarrow$  F  $\models_{as}$  CNot C'
   $\Rightarrow$   $\neg$ no-step backjump-l S and
  cdcl-merged-inv:  $\bigwedge S\ T.$  cdclNOT-merged-bj-learn S T  $\Rightarrow$  inv S  $\Rightarrow$  inv T
begin

abbreviation backjump-conds :: 'v clause  $\Rightarrow$  'v clause  $\Rightarrow$  'v literal  $\Rightarrow$  'st  $\Rightarrow$  'st  $\Rightarrow$  bool
where
  backjump-conds  $\equiv$   $\lambda C\ C'\ L'\ S\ T.$  distinct-mset  $(C' + \{\#L'\#\}) \wedge \neg$ tautology  $(C' + \{\#L'\#\})$ 

Without additional knowledge on backjump-l-cond, it is impossible to have the same invariant.

sublocale dpll-with-backjumping-ops trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT
  inv backjump-conds propagate-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 D where
  S': S'  $\sim$  prepend-trail (Propagated L ()) (reduce-trail-toNOT F (add-clNOT D S))
and
  tr-S: trail S = F' @ Decided K # F and
  C: C  $\in$  # clausesNOT S and
  tr-S-C: trail S  $\models_{as}$  CNot C and
  undef-L: undefined-lit F L and

```

```

atm-L:
  atm-of L ∈ insert (atm-of K) (atms-of-mm (clausesNOT S) ∪ atm-of ‘ (lits-of-l F' ∪ lits-of-l F))
  and
  cls-S-C': clausesNOT S ⊨pm C' + {#L#} and
  F-C': F ⊨as CNot C' and
  dist: distinct-mset (C' + {#L#}) and
  not-tauto: ¬ tautology (C' + {#L#}) and
  cond: backjump-l-cond C C' L S S'
  D = C' + {#L#}
  by (elim backjump-lE) metis
interpret backjumping-ops trail clausesNOT prepend-trail tl-trail add-clsNOT remove-clsNOT
backjump-conds
  by unfold-locales
have ∃ T. backjump S T
apply rule
apply (rule backjump.intros)
  using tr-S apply simp
  apply (rule state-eqNOT-ref)
  using C apply simp
  using tr-S-C apply simp
  using undef-L apply simp
  using atm-L tr-S apply simp
  using cls-S-C' apply simp
  using F-C' apply simp
  using dist not-tauto cond apply simp
done
}
then show ?case using 1 bj-merge-can-jump by meson
qed

end

locale cdclNOT-merge-bj-learn-proxy2 =
  cdclNOT-merge-bj-learn-proxy trail clausesNOT prepend-trail tl-trail add-clsNOT remove-clsNOT
  propagate-conds forget-cond backjump-l-cond inv
for
  trail :: 'st ⇒ ('v, unit) ann-lits and
  clausesNOT :: 'st ⇒ 'v clauses and
  prepend-trail :: ('v, unit) ann-lit ⇒ 'st ⇒ 'st and
  tl-trail :: 'st ⇒ 'st and
  add-clsNOT :: 'v clause ⇒ 'st ⇒ 'st and
  remove-clsNOT :: 'v clause ⇒ 'st ⇒ 'st and
  propagate-conds :: ('v, unit) ann-lit ⇒ 'st ⇒ bool and
  forget-cond :: 'v clause ⇒ 'st ⇒ bool and
  backjump-l-cond :: 'v clause ⇒ 'v clause ⇒ 'v literal ⇒ 'st ⇒ 'st ⇒ bool and
  inv :: 'st ⇒ bool
begin

sublocale conflict-driven-clause-learning-ops trail clausesNOT prepend-trail tl-trail add-clsNOT
  remove-clsNOT inv backjump-conds propagate-conds
λC -. distinct-mset C ∧ ¬tautology C
forget-cond
by unfold-locales
end

locale cdclNOT-merge-bj-learn =

```



```

cdclNOT-merge-bj-learn-proxy2 trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT
propagate-conds forget-cond backjump-l-cond inv
for
  trail :: 'st ⇒ ('v, unit) ann-lits and
  clausesNOT :: 'st ⇒ 'v clauses and
  prepend-trail :: ('v, unit) ann-lit ⇒ 'st ⇒ 'st and
  tl-trail :: 'st ⇒ 'st and
  add-clNOT :: 'v clause ⇒ 'st ⇒ 'st and
  remove-clNOT :: 'v clause ⇒ 'st ⇒ 'st and
  backjump-l-cond :: 'v clause ⇒ 'v clause ⇒ 'v literal ⇒ 'st ⇒ 'st ⇒ bool and
  propagate-conds :: ('v, unit) ann-lit ⇒ 'st ⇒ bool and
  forget-cond :: 'v clause ⇒ 'st ⇒ bool and
  inv :: 'st ⇒ bool +
assumes
  dpll-merge-bj-inv:  $\bigwedge S T. \text{dpll-bj } S T \implies \text{inv } S \implies \text{inv } T$  and
  learn-inv:  $\bigwedge S T. \text{learn } S T \implies \text{inv } S \implies \text{inv } T$ 
begin

sublocale
  conflict-driven-clause-learning trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT
  inv backjump-conds propagate-conds
   $\lambda C -. \text{distinct-mset } C \wedge \neg \text{tautology } C$ 
  forget-cond
apply unfold-locales
using cdclNOT-merged-bj-learn-forgetNOT cdcl-merged-inv learn-inv
by (auto simp add: cdclNOT.simps dpll-merge-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  $\exists C' L D. \text{learn } S (\text{add-cl}_{\text{NOT}} D S)$ 
     $\wedge D = (C' + \{\#L\# \})$ 
     $\wedge \text{backjump } (\text{add-cl}_{\text{NOT}} D S) T$ 
     $\wedge \text{atms-of } (C' + \{\#L\# \}) \subseteq \text{atms-of-mm } (\text{clauses}_{\text{NOT}} S) \cup \text{atm-of } ' (\text{lits-of-l } (\text{trail } S))$ 
proof -
  obtain C F' K F L l C' D where
    tr-S: trail S = F' @ Decided K # F and
    T: T ~ prepend-trail (Propagated L l) (reduce-trail-toNOT F (add-clNOT D S)) and
    C-clS: C ∈ # clausesNOT S and
    tr-S-CNot-C: trail S ⊨as CNot C and
    undef: undefined-lit F L and
    atm-L: atm-of L ∈ atms-of-mm (clausesNOT S) ∪ atm-of ' (lits-of-l (trail S)) and
    clss-C: clausesNOT S ⊨pm D and
    D: D = C' + {#L#}
    F ⊨as CNot C' and
    distinct: distinct-mset D and
    not-tauto: ¬ tautology D
  using bt inv by (elim backjump-lE) simp
  have atms-C': atms-of C' ⊆ atm-of ' (lits-of-l F)
    by (metis D(2) atms-of-def image-subsetI true-annots-CNot-all-atms-defined)
  then have atms-of (C' + {#L#}) ⊆ atms-of-mm (clausesNOT S) ∪ atm-of ' (lits-of-l (trail S))
    using atm-L tr-S by auto
  moreover have learn: learn S (add-clNOT D S)
    apply (rule learn.intros)
    apply (rule clss-C)
    using atms-C' atm-L D 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-cls*_{NOT} *D S*) *T*
apply (*rule backjump.intros*)
using $\langle F \models_{as} CNot\ C' \rangle$ *C-cls-S tr-S-CNot-C undef T distinct not-tauto n-d D*
by (*auto simp*: *tr-S state-eq*_{NOT}-*def simp del*: *state-simp*_{NOT})
ultimately show *?thesis* **using** *D* **by** *blast*
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* clause **and** *L* :: '*v* literal **and** *D* :: '*v* clause **where**

f3: *learn S* (*add-cls*_{NOT} *D S*) \wedge

backjump (*add-cls*_{NOT} *D S*) *T* \wedge

atms-of (*C'* + {*#L#*}) \subseteq *atms-of-mm* (*clauses*_{NOT} *S*) \cup *atm-of* '*lits-of-l* (*trail S*) **and**

D: *D* = *C'* + {*#L#*}

using *n-d backjump-l-learn-backjump*[*OF bt inv*] **by** *blast*

then have *f4*: *cdcl*_{NOT} *S* (*add-cls*_{NOT} *D S*)

using *n-d c-learn* **by** *blast*

have *cdcl*_{NOT} (*add-cls*_{NOT} *D 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-tranclp-cdcl*_{NOT}[*OF cdcl*_{NOT}] *IH*

*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 $n-d IH \langle cdcl_{NOT}^{**} T U \rangle rtranclp-cdcl_{NOT}-inv$ 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 $\mu_C' :: 'v \text{ clause set} \Rightarrow 'st \Rightarrow nat$ **where**
 $\mu_C' A T \equiv \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight T)$

definition $\mu_{DCL}'-merged :: 'v \text{ clause set} \Rightarrow 'st \Rightarrow nat$ **where**
 $\mu_{DCL}'-merged A T \equiv$
 $((2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A)) - \mu_C' A T) * 2 + card (set-mset (clauses_{NOT} T))$

lemma $cdcl_{NOT}-decreasing-measure'$:
assumes
 $cdcl_{NOT}-merged-bj-learn S T$ **and**
 $inv: inv S$ **and**
 $atm-clss: atms-of-mm (clauses_{NOT} S) \subseteq atms-of-ms A$ **and**
 $atm-trail: atm-of \text{ ' lits-of-l } (trail S) \subseteq atms-of-ms A$ **and**
 $n-d: no-dup (trail S)$ **and**
 $fin-A: finite A$
shows $\mu_{DCL}'-merged A T < \mu_{DCL}'-merged A S$
using *assms(1)*

proof *induction*

case $(cdcl_{NOT}-merged-bj-learn-decide_{NOT} T)$
have $clauses_{NOT} S = clauses_{NOT} T$
using $cdcl_{NOT}-merged-bj-learn-decide_{NOT}.hyps$ by *auto*
moreover have
 $(2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))$
 $- \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight T)$
 $< (2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))$
 $- \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight S)$
apply $(rule \text{ dpll-bj-trail-mes-decreasing-prop})$
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 $\mu_{DCL}'-merged-def \mu_C'-def$ by *simp*

next

case $(cdcl_{NOT}-merged-bj-learn-propagate_{NOT} T)$
have $clauses_{NOT} S = clauses_{NOT} T$
using $cdcl_{NOT}-merged-bj-learn-propagate_{NOT}.hyps$
by $(simp add: bj-propagate_{NOT} inv dpll-bj-clauses)$
moreover have
 $(2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))$
 $- \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight T)$
 $< (2 + card (atms-of-ms A)) \wedge (1 + card (atms-of-ms A))$
 $- \mu_C (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight S)$
apply $(rule \text{ dpll-bj-trail-mes-decreasing-prop})$

```

    using inv n-d atm-clss atm-trail fin-A by (simp-all add: bj-propagateNOT
      cdclNOT-merged-bj-learn-propagateNOT.hyps)
  ultimately show ?case
    unfolding  $\mu_{CDCL}'$ -merged-def  $\mu_C'$ -def by simp
next
case (cdclNOT-merged-bj-learn-forgetNOT T)
have card (set-mset (clausesNOT T)) < card (set-mset (clausesNOT S))
  using ⟨forgetNOT S T⟩ by (metis card-Diff1-less clauses-remove-clsNOT finite-set-mset
    forgetNOT.cases linear set-mset-minus-replicate-mset(1) state-eqNOT-def)
moreover
  have trail S = trail T
    using ⟨forgetNOT S T⟩ by (auto elim: forgetNOTE)
  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 T))
  = ((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 S))
    by auto
  ultimately show ?case
    unfolding  $\mu_{CDCL}'$ -merged-def  $\mu_C'$ -def by simp
next
case (cdclNOT-merged-bj-learn-backjump-l T) note bj-l = this(1)
obtain C' L D where
  learn: learn S (add-clsNOT D S) and
  bj: backjump (add-clsNOT D S) T and
  atms-C: atms-of (C' + {#L#})  $\subseteq$  atms-of-mm (clausesNOT S)  $\cup$  atm-of ' (lits-of-l (trail S)) and
  D: D = C' + {#L#}
  using bj-l inv backjump-l-learn-backjump [of S] n-d atm-clss atm-trail by blast
have card-T-S: card (set-mset (clausesNOT T))  $\leq$  1 + card (set-mset (clausesNOT S))
  using bj-l inv by (force elim!: backjump-lE simp: card-insert-if)
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 T))
  < ((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 (add-clsNOT D S)))
  apply (rule dpll-bj-trail-mes-decreasing-prop)
    using bj bj-backjump apply blast
    using cdclNOT.c-learn cdclNOT-inv inv learn apply blast
    using atms-C atm-clss atm-trail D apply (simp add: n-d) apply fast
    using atm-trail n-d apply simp
  apply (simp add: n-d)
  using fin-A apply simp
done
then have ((2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A))
  -  $\mu_C$  (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight T))
  < ((2 + card (atms-of-ms A)) ^ (1 + card (atms-of-ms A))
  -  $\mu_C$  (1 + card (atms-of-ms A)) (2 + card (atms-of-ms A)) (trail-weight S))
  using n-d by auto
then show ?case
  using card-T-S unfolding  $\mu_{CDCL}'$ -merged-def  $\mu_C'$ -def by linarith
qed

lemma wf-cdclNOT-merged-bj-learn:
  assumes
    fin-A: finite A

```

shows $wf \{(T, S).$
 $(inv\ S \wedge atms-of-mm\ (clauses_{NOT}\ S) \subseteq atms-of-ms\ A \wedge atm-of\ 'lits-of-l\ (trail\ S) \subseteq atms-of-ms\ A$
 $\wedge no-dup\ (trail\ S))$
 $\wedge cdcl_{NOT}\text{-merged-bj-learn}\ S\ T\}$
apply (rule $wfP\text{-if-measure}[of\ -\ -\ \mu_{CDCL}'\text{-merged}\ A]$)
using $cdcl_{NOT}\text{-decreasing-measure}'\ fin\text{-}A$ **by** *simp*

lemma $trancpl\text{-}cdcl_{NOT}\text{-}cdcl_{NOT}\text{-}trancpl$:

assumes

$cdcl_{NOT}\text{-merged-bj-learn}^{++}\ S\ T$ **and**

inv : $inv\ S$ **and**

$atm\text{-}clss$: $atms-of-mm\ (clauses_{NOT}\ S) \subseteq atms-of-ms\ A$ **and**

$atm\text{-}trail$: $atm-of\ 'lits-of-l\ (trail\ S) \subseteq atms-of-ms\ A$ **and**

$n\text{-}d$: $no-dup\ (trail\ S)$ **and**

$fin\text{-}A[simp]$: $finite\ A$

shows $(T, S) \in \{(T, S).$

$(inv\ S \wedge atms-of-mm\ (clauses_{NOT}\ S) \subseteq atms-of-ms\ A \wedge atm-of\ 'lits-of-l\ (trail\ S) \subseteq atms-of-ms\ A$
 $\wedge no-dup\ (trail\ S))$
 $\wedge cdcl_{NOT}\text{-merged-bj-learn}\ S\ T\}^+ \text{ (is } - \in ?P^+)$

using $assms(1)$

proof (induction rule: $trancpl\text{-}induct$)

case *base*

then show $?case$ **using** $n\text{-}d\ atm\text{-}clss\ atm\text{-}trail\ inv$ **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 $rtrancpl\text{-}cdcl_{NOT}\text{-merged-bj-learn-is-rtrancpl\text{-}cdcl_{NOT}$)

using $st\ cdcl_{NOT}\ inv\ n\text{-}d\ atm\text{-}clss\ atm\text{-}trail\ inv$ **by** *auto*

have $inv\ T$

apply (rule $rtrancpl\text{-}cdcl_{NOT}\text{-merged-bj-learn-inv$)

using $inv\ st\ cdcl_{NOT}\ n\text{-}d\ atm\text{-}clss\ atm\text{-}trail\ inv$ **by** *auto*

moreover have $atms-of-mm\ (clauses_{NOT}\ T) \subseteq atms-of-ms\ A$

using $rtrancpl\text{-}cdcl_{NOT}\text{-trail-clauses-bound}[OF\ \langle cdcl_{NOT}^{**}\ S\ T \rangle\ inv\ n\text{-}d\ atm\text{-}clss\ atm\text{-}trail]$

by *fast*

moreover have $atm-of\ 'lits-of-l\ (trail\ T) \subseteq atms-of-ms\ A$

using $rtrancpl\text{-}cdcl_{NOT}\text{-trail-clauses-bound}[OF\ \langle cdcl_{NOT}^{**}\ S\ T \rangle\ inv\ n\text{-}d\ atm\text{-}clss\ atm\text{-}trail]$

by *fast*

moreover have $no-dup\ (trail\ T)$

using $rtrancpl\text{-}cdcl_{NOT}\text{-no-dup}[OF\ \langle cdcl_{NOT}^{**}\ S\ T \rangle\ inv\ n\text{-}d]$ **by** *fast*

ultimately have $(U, T) \in ?P$

using $cdcl_{NOT}$ **by** *auto*

then show $?case$ **using** IH **by** (*simp add: trancpl\text{-}into-trancpl2*)

qed

lemma $wf\text{-}trancpl\text{-}cdcl_{NOT}\text{-merged-bj-learn}$:

assumes $finite\ A$

shows $wf \{(T, S).$

$(inv\ S \wedge atms-of-mm\ (clauses_{NOT}\ S) \subseteq atms-of-ms\ A \wedge atm-of\ 'lits-of-l\ (trail\ S) \subseteq atms-of-ms\ A$
 $\wedge no-dup\ (trail\ S))$
 $\wedge cdcl_{NOT}\text{-merged-bj-learn}^{++}\ S\ T\}$

apply (rule $wf\text{-}subset$)

apply (rule $wf\text{-}trancpl[OF\ wf\text{-}cdcl_{NOT}\text{-merged-bj-learn}]$)

using $assms$ **apply** *simp*

using $trancpl\text{-}cdcl_{NOT}\text{-}cdcl_{NOT}\text{-}trancpl[OF\ -\ -\ -\ -\ \langle finite\ A \rangle]$ **by** *auto*

lemma $backjump\text{-}no\text{-}step\text{-}backjump\text{-}l$:

$\text{backjump } S \ T \implies \text{inv } S \implies \neg \text{no-step backjump-l } S$
apply (elim backjumpE)
apply (rule bj-merge-can-jump)
apply auto[7]
by blast

lemma $\text{cdcl}_{\text{NOT-merged-bj-learn-final-state}}$:

fixes $A :: 'v \text{ clause set}$ **and** $S \ T :: 'st$

assumes

$n\text{-s}$: $\text{no-step cdcl}_{\text{NOT-merged-bj-learn}} \ S$ **and**

atms-S : $\text{atms-of-mm} (\text{clauses}_{\text{NOT}} \ S) \subseteq \text{atms-of-ms } A$ **and**

atms-trail : $\text{atm-of } ' \text{ lits-of-l } (\text{trail } S) \subseteq \text{atms-of-ms } A$ **and**

$n\text{-d}$: $\text{no-dup} (\text{trail } S)$ **and**

$\text{finite } A$ **and**

inv : $\text{inv } S$ **and**

decomp : $\text{all-decomposition-implies-m} (\text{clauses}_{\text{NOT}} \ S) (\text{get-all-ann-decomposition} (\text{trail } S))$

shows $\text{unsatisfiable} (\text{set-mset} (\text{clauses}_{\text{NOT}} \ S))$

$\vee (\text{trail } S \models_{\text{asm}} \text{clauses}_{\text{NOT}} \ S \wedge \text{satisfiable} (\text{set-mset} (\text{clauses}_{\text{NOT}} \ S)))$

proof –

let $?N = \text{set-mset} (\text{clauses}_{\text{NOT}} \ S)$

let $?M = \text{trail } S$

consider

$(\text{sat}) \text{ satisfiable } ?N$ **and** $?M \models_{\text{as}} ?N$

| $(\text{sat}') \text{ satisfiable } ?N$ **and** $\neg ?M \models_{\text{as}} ?N$

| $(\text{unsat}) \text{ unsatisfiable } ?N$

by auto

then show $?thesis$

proof cases

case sat' **note** $\text{sat} = \text{this}(1)$ **and** $M = \text{this}(2)$

obtain C **where** $C \in ?N$ **and** $\neg ?M \models_a C$ **using** M **unfolding** true-annots-def **by** auto

obtain $I :: 'v \text{ literal set}$ **where**

$I \models_s ?N$ **and**

cons : $\text{consistent-interp } I$ **and**

tot : $\text{total-over-m } I \ ?N$ **and**

atm-I-N : $\text{atm-of } 'I \subseteq \text{atms-of-ms } ?N$

using sat **unfolding** $\text{satisfiable-def-min}$ **by** auto

let $?I = I \cup \{P \mid P. P \in \text{lits-of-l } ?M \wedge \text{atm-of } P \notin \text{atm-of } 'I\}$

let $?O = \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } ?M \wedge \text{atm-of } (\text{lit-of } L) \notin \text{atms-of-ms } ?N\}$

have cons-I' : $\text{consistent-interp } ?I$

using cons **using** $\langle \text{no-dup } ?M \rangle$ **unfolding** $\text{consistent-interp-def}$

by ($\text{auto simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set lits-of-def}$

$\text{dest!:: no-dup-cannot-not-lit-and-uminus}$)

have tot-I' : $\text{total-over-m } ?I \ (\ ?N \cup \text{unmark-l } ?M)$

using tot atms-of-s-def **unfolding** $\text{total-over-m-def total-over-set-def}$

by ($\text{fastforce simp: image-iff}$)

have $\{P \mid P. P \in \text{lits-of-l } ?M \wedge \text{atm-of } P \notin \text{atm-of } 'I\} \models_s ?O$

using $\langle I \models_s ?N \rangle$ atm-I-N **by** ($\text{auto simp add: atm-of-eq-atm-of true-clss-def lits-of-def}$)

then have $I'\text{-N}$: $?I \models_s ?N \cup ?O$

using $\langle I \models_s ?N \rangle$ $\text{true-clss-union-increase}$ **by** force

have tot' : $\text{total-over-m } ?I \ (\ ?N \cup ?O)$

using atm-I-N tot **unfolding** $\text{total-over-m-def total-over-set-def}$

by ($\text{force simp: lits-of-def elim!:: is-decided-ex-Decided}$)

have atms-N-M : $\text{atms-of-ms } ?N \subseteq \text{atm-of } ' \text{ lits-of-l } ?M$

proof (rule ccontr)

assume $\neg ?thesis$

```

then obtain  $l :: 'v$  where
   $l-N: l \in \text{atms-of-ms } ?N$  and
   $l-M: l \notin \text{atm-of } ' \text{ lits-of-l } ?M$ 
  by auto
have undefined-lit  $?M$  (Pos  $l$ )
  using  $l-M$  by (metis Decided-Propagated-in-iff-in-lits-of-l
    atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set literal.sel(1))
have decideNOT  $S$  (prepend-trail (Decided (Pos  $l$ ))  $S$ )
  by (metis (undefined-lit  $?M$  (Pos  $l$ )) decideNOT.intros  $l-N$  literal.sel(1)
    state-eqNOT-ref)
then show False
  using cdclNOT-merged-bj-learn-decideNOT  $n-s$  by blast
qed

have  $?M \models_{as} CNot\ C$ 
apply (rule all-variables-defined-not-imply-cnot)
  using atms- $N-M$   $\langle C \in ?N \rangle \hookrightarrow ?M \models_a C$  atms-of-atms-of-ms-mono[OF  $\langle C \in ?N \rangle$ ]
  by (auto dest: atms-of-atms-of-ms-mono)
have  $\exists l \in \text{set } ?M. \text{is-decided } l$ 
proof (rule ccontr)
  let  $?O = \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } ?M \wedge \text{atm-of } (\text{lit-of } L) \notin \text{atms-of-ms } ?N\}$ 
  have  $\vartheta[\text{iff}]: \bigwedge I. \text{total-over-m } I \ (\ ?N \cup ?O \cup \text{unmark-l } ?M)$ 
     $\longleftrightarrow \text{total-over-m } I \ (\ ?N \cup \text{unmark-l } ?M)$ 
    unfolding total-over-set-def total-over-m-def atms-of-ms-def by blast
  assume  $\neg ?thesis$ 
  then have [simp]:  $\{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } ?M\}$ 
     $= \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } ?M \wedge \text{atm-of } (\text{lit-of } L) \notin \text{atms-of-ms } ?N\}$ 
    by auto
  then have  $?N \cup ?O \models_{ps} \text{unmark-l } ?M$ 
    using all-decomposition-implies-propagated-lits-are-implied[OF decomp] by auto

  then have  $?I \models_s \text{unmark-l } ?M$ 
    using cons- $I'$   $I'-N$  tot- $I'$   $\langle ?I \models_s ?N \cup ?O \rangle$  unfolding  $\vartheta$  true-clss-clss-def by blast
  then have lits-of-l  $?M \subseteq ?I$ 
    unfolding true-clss-def lits-of-def by auto
  then have  $?M \models_{as} ?N$ 
    using  $I'-N$   $\langle C \in ?N \rangle \hookrightarrow ?M \models_a C$  cons- $I'$  atms- $N-M$ 
    by (meson (trail  $S \models_{as} CNot\ C$ ) 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  $d :: \text{unit}$  and
   $F\ F' :: ('v, \text{unit}) \text{ann-lits}$  where
   $M-K: ?M = F' @ \text{Decided } K \# F$  and
   $nm: \forall f \in \text{set } F'. \neg \text{is-decided } f$ 
  unfolding is-decided-def by (metis (full-types) old.unit.exhaust)
let  $?K = \text{Decided } K :: ('v, \text{unit}) \text{ann-lit}$ 
have  $?K \in \text{set } ?M$ 
  unfolding  $M-K$  by auto
let  $?C = \text{image-mset lit-of } \{\#L \in \#mset\ ?M. \text{is-decided } L \wedge L \neq ?K\} :: 'v \text{ clause}$ 
let  $?C' = \text{set-mset } (\text{image-mset } (\lambda L :: 'v \text{ literal}. \{\#L\}) \ (\ ?C + \text{unmark } ?K))$ 
have  $?N \cup \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } ?M\} \models_{ps} \text{unmark-l } ?M$ 
  using all-decomposition-implies-propagated-lits-are-implied[OF decomp] .
moreover have  $C': ?C' = \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } ?M\}$ 
  unfolding  $M-K$  apply standard
  apply force

```

```

  by auto
ultimately have N-C-M: ?N  $\cup$  ?C'  $\models_{ps}$  unmark-l ?M
  by auto
have N-M-False: ?N  $\cup$  ( $\lambda L. \text{unmark } L$ ) ' (set ?M)  $\models_{ps}$  {{#}}
  using M  $\langle ?M \models_{as} CNot \ C \rangle \langle C \in ?N \rangle$  unfolding true-clss-clss-def true-annots-def Ball-def
  true-annot-def by (metis consistent-CNot-not sup.orderE sup-commute true-clss-def
    true-clss-singleton-lit-of-implies-incl true-clss-union true-clss-union-increase)

have undefined-lit F K using  $\langle no\text{-}dup \ ?M \rangle$  unfolding M-K by (simp add: defined-lit-map)
moreover
  have ?N  $\cup$  ?C'  $\models_{ps}$  {{#}}
  proof -
    have A: ?N  $\cup$  ?C'  $\cup$  unmark-l ?M = ?N  $\cup$  unmark-l ?M
      unfolding M-K by auto
    show ?thesis
      using true-clss-clss-left-right[OF N-C-M, of {{#}}] N-M-False unfolding A by auto
  qed
have ?N  $\models_p$  image-mset uminus ?C + {#-K#}
  unfolding true-clss-clss-def true-clss-clss-def total-over-m-def
  proof (intro allI impI)
    fix I
    assume
      tot: total-over-set I (atms-of-ms (?N  $\cup$  {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  $\{a \in \text{set } (trail \ S). \text{is-decided } a \wedge a \neq \text{Decided } K\} =$ 
       $\text{set } (trail \ S) \cap \{L. \text{is-decided } L \wedge L \neq \text{Decided } K\}$ 
      by auto
    then have tot': total-over-set I
      (atm-of 'lit-of ' (set ?M  $\cap$  {L. is-decided L  $\wedge$  L  $\neq$  Decided K}))
      using tot by (auto simp add: atms-of-uminus-lit-atm-of-lit-of)
    { fix x :: ('v, unit) ann-lit
      assume
        a3: lit-of x  $\notin$  I and
        a1: x  $\in$  set ?M and
        a4: is-decided x and
        a5: x  $\neq$  Decided 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-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  $F \models_{as} CNot \ (image-mset \ minus \ ?C)$ 
    using nm unfolding true-annots-def CNot-def M-K by (auto simp add: lits-of-def)
  ultimately have False
    using bj-merge-can-jump[of S F' K F C -K
      image-mset minus (image-mset lit-of {# L :# mset ?M. is-decided L  $\wedge$  L  $\neq$  Decided 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 clause set and S T :: 'st
  assumes
    full: full cdclNOT-merged-bj-learn S T and
    atms-S: atms-of-mm (clausesNOT S)  $\subseteq$  atms-of-ms A and
    atms-trail: atm-of ' lits-of-l (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 (clausesNOT S) (get-all-ann-decomposition (trail S))
  shows unsatisfiable (set-mset (clausesNOT T))
     $\vee (trail \ T \models_{asm} clauses_{NOT} \ T \wedge \text{satisfiable } (set-mset (clauses_{NOT} \ T)))$ 
proof -
  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: cdclNOT** S T
    using inv rtranclp-cdclNOT-merged-bj-learn-is-rtranclp-cdclNOT-and-inv n-d by auto
  have atms-of-mm (clausesNOT T)  $\subseteq$  atms-of-ms A and atm-of ' lits-of-l (trail T)  $\subseteq$  atms-of-ms A
    using rtranclp-cdclNOT-trail-clauses-bound[OF st inv n-d atms-S atms-trail] by blast+
  moreover have no-dup (trail T)
    using rtranclp-cdclNOT-no-dup inv n-d st by blast
  moreover have inv T
    using rtranclp-cdclNOT-inv inv st by blast
  moreover have all-decomposition-implies-m (clausesNOT T) (get-all-ann-decomposition (trail T))
    using rtranclp-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

```

5.2.7 Instantiations

In this section, we instantiate the previous locales to ensure that the assumption are not contradictory.

```

locale cdclNOT-with-backtrack-and-restarts =
  conflict-driven-clause-learning-learning-before-backjump-only-distinct-learnt
  trail clausesNOT prepend-trail tl-trail add-clNOT remove-clNOT
  inv backjump-conds propagate-conds learn-restrictions forget-restrictions
for
  trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
  clausesNOT :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and

```

```

tl-trail :: 'st ⇒ 'st and
add-clsNOT :: 'v clause ⇒ 'st ⇒ 'st and
remove-clsNOT :: 'v clause ⇒ 'st ⇒ 'st and
inv :: 'st ⇒ bool and
backjump-cons :: 'v clause ⇒ 'v clause ⇒ 'v literal ⇒ 'st ⇒ 'st ⇒ bool and
propagate-cons :: ('v, unit) ann-lit ⇒ 'st ⇒ bool and
learn-restrictions forget-restrictions :: 'v clause ⇒ 'st ⇒ bool
+
fixes f :: nat ⇒ nat
assumes
  unbounded: unbounded f and f-ge-1:  $\bigwedge n. n \geq 1 \implies f\ n \geq 1$  and
  inv-restart:  $\bigwedge S\ T. inv\ S \implies T \sim \text{reduce-trail-to}_{NOT} ([::'a\ list)\ S \implies inv\ T$ 
begin

lemma bound-inv-inv:
  assumes
    inv S and
    n-d: no-dup (trail S) and
    atms-cls-S-A: atms-of-mm (clausesNOT S) ⊆ atms-of-ms A and
    atms-trail-S-A: atm-of ' lits-of-l (trail S) ⊆ atms-of-ms A and
    finite A and
    cdclNOT: cdclNOT S T
  shows
    atms-of-mm (clausesNOT T) ⊆ atms-of-ms A and
    atm-of ' lits-of-l (trail T) ⊆ atms-of-ms A and
    finite A
proof -
  have cdclNOT S T
  using ⟨inv S⟩ cdclNOT by linarith
  then have atms-of-mm (clausesNOT T) ⊆ atms-of-mm (clausesNOT S) ∪ atm-of ' lits-of-l (trail S)
  using ⟨inv S⟩
  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-mm (clausesNOT T) ⊆ atms-of-ms A
  using atms-cls-S-A atms-trail-S-A by blast
next
  show atm-of ' lits-of-l (trail T) ⊆ atms-of-ms A
  by (meson ⟨inv S⟩ atms-cls-S-A atms-trail-S-A cdclNOT cdclNOT-atms-in-trail-in-set n-d)
next
  show finite A
  using ⟨finite A⟩ by simp
qed

sublocale cdclNOT-increasing-restarts-ops λS T. T ∼ reduce-trail-toNOT ([::'a list) S cdclNOT f
  λA S. atms-of-mm (clausesNOT S) ⊆ atms-of-ms A ∧ atm-of ' lits-of-l (trail S) ⊆ atms-of-ms A ∧
  finite A
  μCDCL' λS. inv S ∧ no-dup (trail S)
  μCDCL'-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-μCDCL'-bound; simp)
    apply (rule rtranclp-μCDCL'-bound-decreasing; simp)
    apply auto[]

```

```

    apply auto[]
    using cdclNOT-inv cdclNOT-no-dup apply blast
    using inv-restart apply auto[]
done

lemma cdclNOT-with-restart- $\mu_{CDCL}'$ -le- $\mu_{CDCL}'$ -bound:
  assumes
    cdclNOT: cdclNOT-restart (T, a) (V, b) and
    cdclNOT-inv:
      inv T
      no-dup (trail T) and
    bound-inv:
      atms-of-mm (clausesNOT T)  $\subseteq$  atms-of-ms A
      atm-of ' lits-of-l (trail T)  $\subseteq$  atms-of-ms A
      finite A
  shows  $\mu_{CDCL}' A V \leq \mu_{CDCL}'$ -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 rtrancplp-cdclNOT- $\mu_{CDCL}'$ -bound-reduce-trail-toNOT[of S T])
      using  $\langle (cdcl_{NOT} \rightsquigarrow m) S T \rangle$  apply (fastforce dest!: relpowp-imp-rtrancplp)
      using 1 by auto
  next
  case (2 S T n) note full = this(2)
  show ?case
    apply (rule rtrancplp-cdclNOT- $\mu_{CDCL}'$ -bound)
      using full 2 unfolding full1-def by force+
qed

lemma cdclNOT-with-restart- $\mu_{CDCL}'$ -bound-le- $\mu_{CDCL}'$ -bound:
  assumes
    cdclNOT: cdclNOT-restart (T, a) (V, b) and
    cdclNOT-inv:
      inv T
      no-dup (trail T) and
    bound-inv:
      atms-of-mm (clausesNOT T)  $\subseteq$  atms-of-ms A
      atm-of ' lits-of-l (trail T)  $\subseteq$  atms-of-ms A
      finite A
  shows  $\mu_{CDCL}'$ -bound A V  $\leq \mu_{CDCL}'$ -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  $\mu_{CDCL}'$ -bound A T  $\leq \mu_{CDCL}'$ -bound A S
    apply (rule rtrancplp- $\mu_{CDCL}'$ -bound-decreasing)
      using  $\langle (cdcl_{NOT} \rightsquigarrow m) S T \rangle$  apply (fastforce dest!: relpowp-imp-rtrancplp)
      using 1 by auto
  then show ?case using U unfolding  $\mu_{CDCL}'$ -bound-def by auto
  next
  case (2 S T n) note full = this(2)
  show ?case
    apply (rule rtrancplp- $\mu_{CDCL}'$ -bound-decreasing)
      using full 2 unfolding full1-def by force+
qed

```

sublocale *cdcl_{NOT}-increasing-restarts* - - - - -
 f
 $\lambda S T. T \sim \text{reduce-trail-to}_{NOT} ([\]::'a \text{ list}) S$
 $\lambda A S. \text{atms-of-mm } (\text{clauses}_{NOT} S) \subseteq \text{atms-of-ms } A$
 $\wedge \text{atm-of ' lits-of-l } (\text{trail } S) \subseteq \text{atms-of-ms } A \wedge \text{finite } A$
 $\mu_{CDCL}' \text{ cdcl}_{NOT}$
 $\lambda S. \text{inv } S \wedge \text{no-dup } (\text{trail } S)$
 $\mu_{CDCL}'\text{-bound}$
apply *unfold-locales*
using *cdcl_{NOT}-with-restart- μ_{CDCL}' -le- μ_{CDCL}' -bound* **apply** *simp*
using *cdcl_{NOT}-with-restart- μ_{CDCL}' -bound-le- μ_{CDCL}' -bound* **apply** *simp*
done

lemma *cdcl_{NOT}-restart-all-decomposition-implies*:
assumes *cdcl_{NOT}-restart* $S T$ **and**
 $\text{inv } (\text{fst } S)$ **and**
 $\text{no-dup } (\text{trail } (\text{fst } S))$
 $\text{all-decomposition-implies-m } (\text{clauses}_{NOT} (\text{fst } S)) (\text{get-all-ann-decomposition } (\text{trail } (\text{fst } S)))$
shows
 $\text{all-decomposition-implies-m } (\text{clauses}_{NOT} (\text{fst } T)) (\text{get-all-ann-decomposition } (\text{trail } (\text{fst } T)))$
using *assms* **apply** (*induction*)
using *rtranclp-cdcl_{NOT}-all-decomposition-implies* **by** (*auto dest!: tranclp-into-rtranclp simp: full1-def*)

lemma *rtranclp-cdcl_{NOT}-restart-all-decomposition-implies*:
assumes *cdcl_{NOT}-restart*** $S T$ **and**
 $\text{inv: inv } (\text{fst } S)$ **and**
 $\text{n-d: no-dup } (\text{trail } (\text{fst } S))$ **and**
 $\text{decomp: all-decomposition-implies-m } (\text{clauses}_{NOT} (\text{fst } S)) (\text{get-all-ann-decomposition } (\text{trail } (\text{fst } S)))$
shows
 $\text{all-decomposition-implies-m } (\text{clauses}_{NOT} (\text{fst } T)) (\text{get-all-ann-decomposition } (\text{trail } (\text{fst } T)))$
using *assms(1)*
proof (*induction rule: rtranclp-induct*)
case *base*
then show *?case* **using** *decomp* **by** *simp*
next
case (*step* $T u$) **note** $st = \text{this}(1)$ **and** $r = \text{this}(2)$ **and** $IH = \text{this}(3)$
have $\text{inv } (\text{fst } T)$
using *rtranclp-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv[OF st] inv n-d* **by** *blast*
moreover have $\text{no-dup } (\text{trail } (\text{fst } T))$
using *rtranclp-cdcl_{NOT}-with-restart-cdcl_{NOT}-inv[OF st] inv n-d* **by** *blast*
ultimately show *?case*
using *cdcl_{NOT}-restart-all-decomposition-implies* $r IH n-d$ **by** *fast*
qed

lemma *cdcl_{NOT}-restart-sat-ext-iff*:
assumes
 $st: \text{cdcl}_{NOT}\text{-restart } S T$ **and**
 $n-d: \text{no-dup } (\text{trail } (\text{fst } S))$ **and**
 $inv: \text{inv } (\text{fst } S)$
shows $I \models_{\text{sextm}} \text{clauses}_{NOT} (\text{fst } S) \longleftrightarrow I \models_{\text{sextm}} \text{clauses}_{NOT} (\text{fst } T)$
using *assms*
proof (*induction*)
case (*restart-step* $m S T n U$)
then show *?case*

```

    using rtrancpl-cdclNOT-bj-sat-ext-iff n-d by (fastforce dest!: relpoup-imp-rtrancpl)
next
case restart-full
then show ?case using rtrancpl-cdclNOT-bj-sat-ext-iff unfolding full1-def
by (fastforce dest!: trancpl-into-rtrancpl)
qed

lemma rtrancpl-cdclNOT-restart-sat-ext-iff:
fixes S T :: 'st × nat
assumes
  st: cdclNOT-restart** S T and
  n-d: no-dup (trail (fst S)) and
  inv: inv (fst S)
shows I ⊨sextm clausesNOT (fst S) ⟷ I ⊨sextm clausesNOT (fst T)
using st
proof (induction)
case base
then show ?case by simp
next
case (step T U) note st = this(1) and r = this(2) and IH = this(3)
have inv (fst T)
  using rtrancpl-cdclNOT-with-restart-cdclNOT-inv[OF st] inv n-d by blast+
moreover have no-dup (trail (fst T))
  using rtrancpl-cdclNOT-with-restart-cdclNOT-inv rtrancpl-cdclNOT-no-dup st inv n-d by blast
ultimately show ?case
  using cdclNOT-restart-sat-ext-iff[OF r] IH by blast
qed

```

```

theorem full-cdclNOT-restart-backjump-final-state:
fixes A :: 'v clause set and S T :: 'st
assumes
  full: full cdclNOT-restart (S, n) (T, m) and
  atms-S: atms-of-mm (clausesNOT S) ⊆ atms-of-ms A and
  atms-trail: atm-of ' lits-of-l (trail S) ⊆ atms-of-ms A and
  n-d: no-dup (trail S) and
  fin-A[simp]: finite A and
  inv: inv S and
  decomp: all-decomposition-implies-m (clausesNOT S) (get-all-ann-decomposition (trail S))
shows unsatisfiable (set-mset (clausesNOT S))
  ∨ (lits-of-l (trail T) ⊨sextm clausesNOT S ∧ satisfiable (set-mset (clausesNOT S)))
proof -
have st: cdclNOT-restart** (S, n) (T, m) and
  n-s: no-step cdclNOT-restart (T, m)
  using full unfolding full-def by fast+
have binv-T: atms-of-mm (clausesNOT T) ⊆ atms-of-ms A
  atm-of ' lits-of-l (trail T) ⊆ atms-of-ms A
  using rtrancpl-cdclNOT-with-restart-bound-inv[OF st, of A] inv n-d atms-S atms-trail
  by auto
moreover have inv-T: no-dup (trail T) inv T
  using rtrancpl-cdclNOT-with-restart-cdclNOT-inv[OF st] inv n-d by auto
moreover have all-decomposition-implies-m (clausesNOT T) (get-all-ann-decomposition (trail T))
  using rtrancpl-cdclNOT-restart-all-decomposition-implies[OF st] inv n-d
  decomp by auto
ultimately have T: unsatisfiable (set-mset (clausesNOT T))
  ∨ (trail T ⊨asm clausesNOT T ∧ satisfiable (set-mset (clausesNOT T)))
  using no-step-cdclNOT-restart-no-step-cdclNOT[of (T, m) A] n-s

```

```

  cdclNOT-final-state[of  $T$   $A$ ] unfolding cdclNOT-NOT-all-inv-def by auto
have eq-sat- $S$ - $T$ :  $\bigwedge I. I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} S \longleftrightarrow I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} T$ 
  using rtrancpl-cdclNOT-restart-sat-ext-iff[ $OF$   $st$ ] inv  $n$ -d  $\text{atms}$ - $S$ 
     $\text{atms}$ -trail by auto
have cons- $T$ : consistent-interp (lits-of-l (trail  $T$ ))
  using inv- $T$ (1) distinct-consistent-interp by blast
consider
  (unsat) unsatisfiable (set-mset (clausesNOT  $T$ ))
  | (sat) trail  $T \models_{\text{asm}} \text{clauses}_{\text{NOT}} T$  and satisfiable (set-mset (clausesNOT  $T$ ))
  using  $T$  by blast
then show ?thesis
proof cases
  case unsat
  then have unsatisfiable (set-mset (clausesNOT  $S$ ))
    using eq-sat- $S$ - $T$  consistent-true-clss-ext-satisfiable true-clss-imp-true-clss-ext
    unfolding satisfiable-def by blast
  then show ?thesis by fast
next
  case sat
  then have lits-of-l (trail  $T$ )  $\models_{\text{sextm}} \text{clauses}_{\text{NOT}} S$ 
    using rtrancpl-cdclNOT-restart-sat-ext-iff[ $OF$   $st$ ] inv  $n$ -d  $\text{atms}$ - $S$ 
     $\text{atms}$ -trail by (auto simp: true-clss-imp-true-clss-ext true-annots-true-clss)
  moreover then have satisfiable (set-mset (clausesNOT  $S$ ))
    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

```

The restart does only reset the trail, contrary to Weidenbach's version where forget and restart are always combined. But there is a forget rule.

```

locale cdclNOT-merge-bj-learn-with-backtrack-restarts =
  cdclNOT-merge-bj-learn trail clausesNOT prepend-trail tl-trail add-clssNOT remove-clssNOT
   $\lambda C C' L' S T. \text{distinct-mset } (C' + \{\#L'\# \}) \wedge \text{backjump-l-cond } C C' L' S T$ 
  propagate-conds forget-conds inv
for
  trail :: 'st  $\Rightarrow$  ('v, unit) ann-lits and
  clausesNOT :: 'st  $\Rightarrow$  'v clauses and
  prepend-trail :: ('v, unit) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: 'st  $\Rightarrow$  'st and
  add-clssNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  remove-clssNOT :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st and
  propagate-conds :: ('v, unit) ann-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  $\Rightarrow$  '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:  $\bigwedge S T. \text{inv } S \Rightarrow T \sim \text{reduce-trail-to}_{\text{NOT}} \square S \Rightarrow \text{inv } T$ 
begin

```

definition not-simplified-clss :: 'b literal multiset multiset \Rightarrow 'b literal multiset multiset
where
 not-simplified-clss $A \equiv \{\#C \in \# A. C \notin \text{simple-clss } (\text{atms-of-mm } A)\#\}$

lemma *not-simplified-cls-tautology-distinct-mset*:

not-simplified-cls $A = \{\#C \in \# A. \text{tautology } C \vee \neg \text{distinct-mset } C\# \}$

unfolding *not-simplified-cls-def* **by** (rule *filter-mset-cong*) (auto *simp*: *simple-clss-def*)

lemma *simple-clss-or-not-simplified-cls*:

assumes *atms-of-mm* (*clauses*_{NOT} *S*) \subseteq *atms-of-ms* *A* **and**

$x \in \# \text{clauses}_{NOT} S$ **and** *finite* *A*

shows $x \in \text{simple-clss} (\text{atms-of-ms } A) \vee x \in \# \text{not-simplified-cls} (\text{clauses}_{NOT} S)$

proof –

consider

(*simpl*) $\neg \text{tautology } x$ **and** *distinct-mset* *x*

| (*n-simp*) *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*
subsetCE)

then show ?thesis **by** *blast*

next

case *n-simp*

then have $x \in \# \text{not-simplified-cls} (\text{clauses}_{NOT} S)$

using $\langle x \in \# \text{clauses}_{NOT} S \rangle$ **unfolding** *not-simplified-cls-tautology-distinct-mset* **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-mm* (*clauses*_{NOT} *S*) \subseteq *atms-of-ms* *A* **and**

atms-trail: *atm-of* (*lits-of-l* (*trail* *S*)) \subseteq *atms-of-ms* *A* **and**

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

fin-A[*simp*]: *finite* *A*

shows *set-mset* (*clauses*_{NOT} *T*) \subseteq *set-mset* (*not-simplified-cls* (*clauses*_{NOT} *S*))

$\cup \text{simple-clss} (\text{atms-of-ms } A)$

using *assms*

proof (*induction* rule: *cdcl_{NOT}-merged-bj-learn.induct*)

case *cdcl_{NOT}-merged-bj-learn-decide_{NOT}*

then show ?case **using** *dpll-bj-clauses* **by** (*force* *dest*!: *simple-clss-or-not-simplified-cls*)

next

case *cdcl_{NOT}-merged-bj-learn-propagate_{NOT}*

then show ?case **using** *dpll-bj-clauses* **by** (*force* *dest*!: *simple-clss-or-not-simplified-cls*)

next

case *cdcl_{NOT}-merged-bj-learn-forget_{NOT}*

then show ?case **using** *clauses-remove-cls_{NOT}* **unfolding** *state-eq_{NOT}-def*

by (*force* *elim*!: *forget_{NOT}E* *dest*: *simple-clss-or-not-simplified-cls*)

next

case (*cdcl_{NOT}-merged-bj-learn-backjump-l* *T*) **note** *bj* = *this*(1) **and** *inv* = *this*(2) **and**

atms-clss = *this*(3) **and** *atms-trail* = *this*(4) **and** *n-d* = *this*(5)

have *cdcl_{NOT}*** *S* *T*

apply (rule *rtrancpl-cdcl_{NOT}-merged-bj-learn-is-rtrancpl-cdcl_{NOT}*)
using *bj inv cdcl_{NOT}-merged-bj-learn.simps n-d* **by** *blast+*
have *atm-of* ‘(*lits-of-l* (trail *T*)) \subseteq *atms-of-ms* *A*
using *rtrancpl-cdcl_{NOT}-trail-clauses-bound*[*OF* ‘*cdcl_{NOT}** S T*’] *inv atm-trail atm-clss*
n-d **by** *auto*
have *atms-of-mm* (*clauses_{NOT} T*) \subseteq *atms-of-ms* *A*
using *rtrancpl-cdcl_{NOT}-trail-clauses-bound*[*OF* ‘*cdcl_{NOT}** S T*’] *inv n-d atm-clss atm-trail*
by *fast*
moreover have *no-dup* (trail *T*)
using *rtrancpl-cdcl_{NOT}-no-dup*[*OF* ‘*cdcl_{NOT}** S T*’] *inv n-d* **by** *fast*

obtain *F' K F L l C' C D* **where**
tr-S: trail *S* = *F' @ Decided K # F* **and**
T: *T* \sim *prepend-trail* (*Propagated L l*) (*reduce-trail-to_{NOT} F* (*add-cl_{NOT} D S*)) **and**
C \in *# clauses_{NOT} S* **and**
trail S \models_{as} *CNot C* **and**
undef: *undefined-lit F L* **and**
clauses_{NOT} S \models_{pm} *C' + {#L#}* **and**
F \models_{as} *CNot C'* **and**
D: *D* = *C' + {#L#}* **and**
dist: *distinct-mset* (*C' + {#L#}*) **and**
tauto: \neg *tautology* (*C' + {#L#}*) **and**
backjump-l-cond C C' L S T
using ‘*backjump-l S T*’ **apply** (*elim backjump-lE*) **by** *auto*

have *atms-of C' \subseteq atm-of* ‘(*lits-of-l F*)
using ‘*F* \models_{as} *CNot C'*’ **by** (*simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set*
atms-of-def image-subset-iff in-CNot-implies-uminus(2))
then have *atms-of* (*C' + {#L#}*) \subseteq *atms-of-ms A*
using *T* ‘*atm-of* ‘*lits-of-l* (trail *T*) \subseteq *atms-of-ms A*’ *tr-S undef n-d* **by** *auto*
then have *simple-clss* (*atms-of* (*C' + {#L#}*)) \subseteq *simple-clss* (*atms-of-ms A*)
apply – **by** (rule *simple-clss-mono*) (*simp-all*)
then have *C' + {#L#}* \in *simple-clss* (*atms-of-ms A*)
using *distinct-mset-not-tautology-implies-in-simple-clss*[*OF dist tauto*]
by *auto*
then show ?*case*
using *T inv atm-clss undef tr-S n-d D* **by** (*force dest!: simple-clss-or-not-simplified-clss*)
qed

lemma *cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*:
assumes *cdcl_{NOT}-merged-bj-learn S T*
shows *not-simplified-clss* (*clauses_{NOT} T*) \subseteq *# not-simplified-clss* (*clauses_{NOT} S*)
using *assms apply induction*
prefer 4
unfolding *not-simplified-clss-tautology-distinct-mset* **apply** (*auto elim!: backjump-lE forget_{NOT}E*)[3]
by (*elim backjump-lE*) *auto*

lemma *rtrancpl-cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*:
assumes *cdcl_{NOT}-merged-bj-learn** S T*
shows *not-simplified-clss* (*clauses_{NOT} T*) \subseteq *# not-simplified-clss* (*clauses_{NOT} S*)
using *assms apply induction*
apply *simp*
by (*drule cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*) *auto*

lemma *rtrancpl-cdcl_{NOT}-merged-bj-learn-clauses-bound*:
assumes

$cdcl_{NOT}$ -merged-bj-learn** S T and
 inv S and
 $atms$ -of- mm ($clauses_{NOT}$ S) \subseteq $atms$ -of- ms A and
 atm -of ‘($lits$ -of- l ($trail$ S)) \subseteq $atms$ -of- ms A and
 n - d : no -dup ($trail$ S) and
 $finite[simp]$: $finite$ A
shows set - $mset$ ($clauses_{NOT}$ T) \subseteq set - $mset$ (not - $simplified$ - cls ($clauses_{NOT}$ 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 $cdcl_{NOT} = this(2)$ 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 $finite$ - cls - $S = this(7)$
have st' : $cdcl_{NOT}$ ** S T
using inv $rtranclp$ - $cdcl_{NOT}$ -merged-bj-learn-is- $rtranclp$ - $cdcl_{NOT}$ -and- inv st n - d **by** *blast*
have inv T
using inv $rtranclp$ - $cdcl_{NOT}$ -merged-bj-learn- inv st n - d **by** *blast*
moreover
have $atms$ -of- mm ($clauses_{NOT}$ T) \subseteq $atms$ -of- ms A and
 atm -of ‘ $lits$ -of- l ($trail$ T) \subseteq $atms$ -of- ms A
using $rtranclp$ - $cdcl_{NOT}$ -trail- $clauses$ -bound[$OF\ st'$] inv $atms$ - $clss$ - S $atms$ - $trail$ - S n - d
by *blast+*
moreover moreover have no -dup ($trail$ T)
using $rtranclp$ - $cdcl_{NOT}$ - no -dup[$OF\ \langle cdcl_{NOT}$ ** $S\ T \rangle$ $inv\ n$ - d] **by** *fast*
ultimately have set - $mset$ ($clauses_{NOT}$ U)
 \subseteq set - $mset$ (not - $simplified$ - cls ($clauses_{NOT}$ T)) \cup $simple$ - $clss$ ($atms$ -of- ms A)
using $cdcl_{NOT}$ $finite$ $cdcl_{NOT}$ -merged-bj-learn- $clauses$ -bound
by (*auto intro!*: $cdcl_{NOT}$ -merged-bj-learn- $clauses$ -bound)
moreover have set - $mset$ (not - $simplified$ - cls ($clauses_{NOT}$ T))
 \subseteq set - $mset$ (not - $simplified$ - cls ($clauses_{NOT}$ S))
using $rtranclp$ - $cdcl_{NOT}$ -merged-bj-learn- not - $simplified$ - $decreasing$ [$OF\ st$] **by** *auto*
ultimately show ?*case* **using** IH inv $atms$ - $clss$ - S
by (*auto dest!*: $simple$ - $clss$ -or- not - $simplified$ - cls)
qed

abbreviation μ_{CDCL}' -bound **where**
 μ_{CDCL}' -bound A $T \equiv ((2 + card\ (atms$ -of- $ms\ A)) \wedge (1 + card\ (atms$ -of- $ms\ A))) * 2$
 $+ card\ (set$ - $mset\ (not$ - $simplified$ - cls ($clauses_{NOT}$ T)))

lemma $rtranclp$ - $cdcl_{NOT}$ -merged-bj-learn- $clauses$ -bound-card:

assumes

$cdcl_{NOT}$ -merged-bj-learn** S T and
 inv S and
 $atms$ -of- mm ($clauses_{NOT}$ S) \subseteq $atms$ -of- ms A and
 atm -of ‘($lits$ -of- l ($trail$ S)) \subseteq $atms$ -of- ms A and
 n - d : no -dup ($trail$ S) and
 $finite$: $finite$ A

shows μ_{CDCL}' -merged A $T \leq \mu_{CDCL}'$ -bound A S

proof –

have set - $mset$ ($clauses_{NOT}$ T) \subseteq set - $mset$ (not - $simplified$ - cls ($clauses_{NOT}$ S))
 \cup $simple$ - $clss$ ($atms$ -of- ms A)
using $rtranclp$ - $cdcl_{NOT}$ -merged-bj-learn- $clauses$ -bound[$OF\ assms$] .
moreover have $card$ (set - $mset$ (not - $simplified$ - cls ($clauses_{NOT}$ S))

$\cup \text{simple-clss } (\text{atms-of-ms } A)$
 $\leq \text{card } (\text{set-mset } (\text{not-simplified-clss}(\text{clauses}_{NOT} S))) + 3 \wedge \text{card } (\text{atms-of-ms } A)$
by (*meson* *Nat.le-trans* *atms-of-ms-finite* *simple-clss-card* *card-Un-le* *finite* *nat-add-left-cancel-le*)
ultimately have $\text{card } (\text{set-mset } (\text{clauses}_{NOT} T))$
 $\leq \text{card } (\text{set-mset } (\text{not-simplified-clss}(\text{clauses}_{NOT} S))) + 3 \wedge \text{card } (\text{atms-of-ms } A)$
by (*meson* *Nat.le-trans* *atms-of-ms-finite* *simple-clss-finite* *card-mono* *finite-UnI* *finite-set-mset* *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 *cdcl_{NOT}-increasing-restarts-ops* $\lambda S T. T \sim \text{reduce-trail-to}_{NOT} ([::'a \text{ list}] S$
cdcl_{NOT}-merged-bj-learn *f*
 $\lambda A S. \text{atms-of-mm } (\text{clauses}_{NOT} S) \subseteq \text{atms-of-ms } A$
 $\wedge \text{atm-of ' lits-of-l } (\text{trail } S) \subseteq \text{atms-of-ms } A \wedge \text{finite } A$
 $\mu_{CDCL}'\text{-merged}$
 $\lambda S. \text{inv } S \wedge \text{no-dup } (\text{trail } S)$
 $\mu_{CDCL}'\text{-bound}$
apply *unfold-locales*
using *unbounded apply simp*
using *f-ge-1 apply force*
apply (*blast* *dest!:* *cdcl_{NOT}-merged-bj-learn-is-tranclp-cdcl_{NOT}* *tranclp-into-rtranclp* *rtranclp-cdcl_{NOT}-trail-clauses-bound*)
apply (*simp* *add:* *cdcl_{NOT}-decreasing-measure'*)
using *rtranclp-cdcl_{NOT}-merged-bj-learn-clauses-bound-card* **apply** *blast*
apply (*drule* *rtranclp-cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*)
apply (*auto* *simp:* *card-mono set-mset-mono*)[]
apply *simp*
apply *auto*[]
using *cdcl_{NOT}-merged-bj-learn-no-dup-inv* *cdcl-merged-inv* **apply** *blast*
apply (*auto* *simp:* *inv-restart*)[]
done

lemma *cdcl_{NOT}-restart- μ_{CDCL}' -merged-le- μ_{CDCL}' -bound:*

assumes
cdcl_{NOT}-restart *T V*
inv (*fst* *T*) **and**
no-dup (*trail* (*fst* *T*)) **and**
atms-of-mm (*clauses_{NOT}* (*fst* *T*)) $\subseteq \text{atms-of-ms } A$ **and**
atm-of ' lits-of-l (*trail* (*fst* *T*)) $\subseteq \text{atms-of-ms } A$ **and**
finite *A*
shows $\mu_{CDCL}'\text{-merged } A (\text{fst } V) \leq \mu_{CDCL}'\text{-bound } A (\text{fst } T)$
using *assms*
proof *induction*
case (*restart-full* *S T n*)
show *?case*
unfolding *fst-conv*
apply (*rule* *rtranclp-cdcl_{NOT}-merged-bj-learn-clauses-bound-card*)
using *restart-full* **unfolding** *full1-def* **by** (*force* *dest!:* *tranclp-into-rtranclp*) +
next
case (*restart-step* *m S T n U*) **note** *st = this(1)* **and** *U = this(3)* **and** *inv = this(4)* **and**
n-d = this(5) **and** *atms-clss = this(6)* **and** *atms-trail = this(7)* **and** *finite = this(8)*
then have *st': cdcl_{NOT}-merged-bj-learn** S T*

```

  by (blast dest: relpoup-imp-rtrancpl)
then have st'': cdclNOT** S T
  using inv n-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-d by auto
then have inv U
  using U by (auto simp: inv-restart)
have atms-of-mm (clausesNOT T)  $\subseteq$  atms-of-ms A
  using rtrancpl-cdclNOT-trail-clauses-bound[OF st''] inv atms-clss atms-trail n-d
  by simp
then have atms-of-mm (clausesNOT U)  $\subseteq$  atms-of-ms A
  using U by simp
have not-simplified-cls (clausesNOT U)  $\subseteq$  # not-simplified-cls (clausesNOT T)
  using  $\langle U \sim \text{reduce-trail-to}_{\text{NOT}} [] T \rangle$  by auto
moreover have not-simplified-cls (clausesNOT T)  $\subseteq$  # not-simplified-cls (clausesNOT S)
  apply (rule rtrancpl-cdclNOT-merged-bj-learn-not-simplified-decreasing)
  using  $\langle (\text{cdcl}_{\text{NOT}}\text{-merged-bj-learn } \widetilde{m}) S T \rangle$  by (auto dest!: relpoup-imp-rtrancpl)
ultimately have U-S: not-simplified-cls (clausesNOT U)  $\subseteq$  # not-simplified-cls (clausesNOT S)
  by auto

have (set-mset (clausesNOT U))
 $\subseteq$  set-mset (not-simplified-cls (clausesNOT 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  $\langle \text{atms-of-mm (clauses}_{\text{NOT}} U) \subseteq \text{atms-of-ms A} \rangle$  apply simp
  using U apply simp
  using U apply simp
  using finite apply simp
done
then have f1: card (set-mset (clausesNOT U))  $\leq$  card (set-mset (not-simplified-cls (clausesNOT U))
 $\cup$  simple-clss (atms-of-ms A))
  by (simp add: simple-clss-finite card-mono local.finite)

moreover have set-mset (not-simplified-cls (clausesNOT U))  $\cup$  simple-clss (atms-of-ms A)
 $\subseteq$  set-mset (not-simplified-cls (clausesNOT S))  $\cup$  simple-clss (atms-of-ms A)
  using U-S by auto
then have f2:
  card (set-mset (not-simplified-cls (clausesNOT U))  $\cup$  simple-clss (atms-of-ms A))
 $\leq$  card (set-mset (not-simplified-cls (clausesNOT S))  $\cup$  simple-clss (atms-of-ms A))
  by (simp add: simple-clss-finite card-mono local.finite)

moreover have card (set-mset (not-simplified-cls (clausesNOT S))
 $\cup$  simple-clss (atms-of-ms A))
 $\leq$  card (set-mset (not-simplified-cls (clausesNOT S))) + card (simple-clss (atms-of-ms A))
  using card-Un-le by blast
moreover have card (simple-clss (atms-of-ms A))  $\leq$  3  $\wedge$  card (atms-of-ms A)
  using atms-of-ms-finite simple-clss-card local.finite by blast
ultimately have card (set-mset (clausesNOT U))
 $\leq$  card (set-mset (not-simplified-cls (clausesNOT S))) + 3  $\wedge$  card (atms-of-ms A)
  by linarith
then show ?case unfolding  $\mu_{\text{CDCL}}'$ -merged-def by auto
qed

```

lemma cdcl_{NOT}-restart- μ_{CDCL}' -bound-le- μ_{CDCL}' -bound:

assumes
cdcl_{NOT}-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 *not-simplified-cls* (*clauses_{NOT}* T) $\subseteq\#$ *not-simplified-cls* (*clauses_{NOT}* S)
apply (*rule* *rtrancpl-cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*)
using $\langle \text{full1 } \text{cdcl}_{NOT}\text{-merged-bj-learn } S \text{ } T \rangle$ **unfolding** *full1-def*
by (*auto* *dest*: *trancpl-into-rtrancpl*)
then show ?*case* **by** (*auto* *simp*: *card-mono set-mset-mono*)
next
case (*restart-step* m S T n U) **note** $st = \text{this}(1)$ **and** $U = \text{this}(3)$ **and** $n-d = \text{this}(4)$ **and**
 $inv = \text{this}(5)$
then have st' : *cdcl_{NOT}-merged-bj-learn*^{**} S T
by (*blast* *dest*: *relpowp-imp-rtrancpl*)
then have st'' : *cdcl_{NOT}*^{**} S T
using inv $n-d$ **apply** – **by** (*rule* *rtrancpl-cdcl_{NOT}-merged-bj-learn-is-rtrancpl-cdcl_{NOT}*) *auto*
have inv T
apply (*rule* *rtrancpl-cdcl_{NOT}-merged-bj-learn-inv*)
using inv st' $n-d$ **by** *auto*
then have inv U
using U **by** (*auto* *simp*: *inv-restart*)
have *not-simplified-cls* (*clauses_{NOT}* U) $\subseteq\#$ *not-simplified-cls* (*clauses_{NOT}* T)
using $\langle U \sim \text{reduce-trail-to}_{NOT} [] :: 'a \text{ list} \rangle$ **by** *auto*
moreover have *not-simplified-cls* (*clauses_{NOT}* T) $\subseteq\#$ *not-simplified-cls* (*clauses_{NOT}* S)
apply (*rule* *rtrancpl-cdcl_{NOT}-merged-bj-learn-not-simplified-decreasing*)
using $\langle (\text{cdcl}_{NOT}\text{-merged-bj-learn } \widetilde{\sim} m) S \text{ } T \rangle$ **by** (*auto* *dest*!: *relpowp-imp-rtrancpl*)
ultimately have $U\text{-}S$: *not-simplified-cls* (*clauses_{NOT}* U) $\subseteq\#$ *not-simplified-cls* (*clauses_{NOT}* S)
by *auto*
then show ?*case* **by** (*auto* *simp*: *card-mono set-mset-mono*)
qed

sublocale *cdcl_{NOT}-increasing-restarts* - - - - f
 λS T . $T \sim \text{reduce-trail-to}_{NOT} ([] :: 'a \text{ list})$ S
 λA S . *atms-of-mm* (*clauses_{NOT}* S) \subseteq *atms-of-ms* A
 \wedge *atm-of* ' *lits-of-l* (*trail* S) \subseteq *atms-of-ms* $A \wedge \text{finite } A$
 $\mu_{CDCL}'\text{-merged } \text{cdcl}_{NOT}\text{-merged-bj-learn}$
 λS . inv $S \wedge \text{no-dup } (\text{trail } S)$
 λA T . $((2 + \text{card } (\text{atms-of-ms } A)) \wedge (1 + \text{card } (\text{atms-of-ms } A))) * 2$
 $+ \text{card } (\text{set-mset } (\text{not-simplified-cls}(\text{clauses}_{NOT} \text{ } T)))$
 $+ 3 \wedge \text{card } (\text{atms-of-ms } A)$
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 $I \models_{\text{sextm}} \text{clauses}_{NOT} \text{ (fst } S) \longleftrightarrow I \models_{\text{sextm}} \text{clauses}_{NOT} \text{ (fst } T)$

```

using assms
proof (induction rule: cdclNOT-restart.induct)
  case (restart-full S T n)
  then have cdclNOT-merged-bj-learn** S T
    by (simp add: tranclp-into-rtranclp full1-def)
  then show ?case
    using rtranclp-cdclNOT-bj-sat-ext-iff restart-full.prems(1,2)
    rtranclp-cdclNOT-merged-bj-learn-is-rtranclp-cdclNOT by auto
next
  case (restart-step m S T n U)
  then have cdclNOT-merged-bj-learn** S T
    by (auto simp: tranclp-into-rtranclp full1-def dest!: relpowp-imp-rtranclp)
  then have  $I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} S \longleftrightarrow I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} T$ 
    using rtranclp-cdclNOT-bj-sat-ext-iff restart-step.prems(1,2)
    rtranclp-cdclNOT-merged-bj-learn-is-rtranclp-cdclNOT by auto
  moreover have  $I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} T \longleftrightarrow I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} U$ 
    using restart-step.hyps(3) by auto
  ultimately show ?case by auto
qed

lemma rtranclp-cdclNOT-restart-eq-sat-iff:
  assumes
    cdclNOT-restart** S T and
    inv: inv (fst S) and n-d: no-dup(trail (fst S))
  shows  $I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} (\text{fst } S) \longleftrightarrow I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} (\text{fst } T)$ 
  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  $I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} (\text{fst } T) \longleftrightarrow I \models_{\text{sextm}} \text{clauses}_{\text{NOT}} (\text{fst } U)$ 
    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 (clausesNOT (fst S))
    (get-all-ann-decomposition (trail (fst S)))
  shows all-decomposition-implies-m (clausesNOT (fst T))
    (get-all-ann-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 rtrancp-cdclNOT-cdclNOT-inv[OF st] inv n-d by auto
  then show ?case
    using rtrancp-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 *rtrancp-cdcl_{NOT}-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 (clausesNOT (fst S))
    (get-all-ann-decomposition (trail (fst S)))
shows all-decomposition-implies-m (clausesNOT (fst T))
  (get-all-ann-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 rtrancp-cdclNOT-with-restart-cdclNOT-inv using st inv n-d by blast+
then show ?case
  using cdclNOT-restart-all-decomposition-implies-m[OF cdcl] IH by auto
qed

```

lemma *full-cdcl_{NOT}-restart-normal-form:*

```

assumes
  full: full cdclNOT-restart S T and
  inv: inv (fst S) and n-d: no-dup(trail (fst S)) and
  decomp: all-decomposition-implies-m (clausesNOT (fst S))
    (get-all-ann-decomposition (trail (fst S))) and
  atms-cls: atms-of-mm (clausesNOT (fst S)) ⊆ atms-of-ms A and
  atms-trail: atm-of ' lits-of-l (trail (fst S)) ⊆ atms-of-ms A and
  fin: finite A
shows unsatisfiable (set-mset (clausesNOT (fst S)))
  ∨ lits-of-l (trail (fst T)) ⊨ sextm clausesNOT (fst S) ∧
  satisfiable (set-mset (clausesNOT (fst S)))
proof -
have inv-T: inv (fst T) and n-d-T: no-dup (trail (fst T))
  using rtrancp-cdclNOT-with-restart-cdclNOT-inv using full inv n-d unfolding full-def by blast+
moreover have
  atms-cls-T: atms-of-mm (clausesNOT (fst T)) ⊆ atms-of-ms A and
  atms-trail-T: atm-of ' lits-of-l (trail (fst T)) ⊆ atms-of-ms A
  using rtrancp-cdclNOT-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-step cdclNOT-merged-bj-learn (fst T)
  apply -
  apply (rule no-step-cdclNOT-restart-no-step-cdclNOT[of - A])
    using full unfolding full-def apply simp
  apply simp
  using fin apply simp

```

```

done
moreover have all-decomposition-implies-m (clausesNOT (fst T))
  (get-all-ann-decomposition (trail (fst T)))
  using rtrancpl-cdclNOT-restart-all-decomposition-implies-m[of S T] inv n-d decomp
  full unfolding full-def by auto
ultimately have unsatisfiable (set-mset (clausesNOT (fst T)))
  ∨ trail (fst T) ⊨asm clausesNOT (fst T) ∧ satisfiable (set-mset (clausesNOT (fst T)))
  apply -
  apply (rule cdclNOT-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-mset (clausesNOT (fst T)))
  | (sat) trail (fst T) ⊨asm clausesNOT (fst T) and satisfiable (set-mset (clausesNOT (fst T)))
  by auto
then show unsatisfiable (set-mset (clausesNOT (fst S)))
  ∨ lits-of-l (trail (fst T)) ⊨sextm clausesNOT (fst S) ∧
  satisfiable (set-mset (clausesNOT (fst S)))
proof cases
  case unsat
  then have unsatisfiable (set-mset (clausesNOT (fst S)))
  unfolding satisfiable-def apply auto
  using rtrancpl-cdclNOT-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-of-l (trail (fst T)) ⊨sextm clausesNOT (fst T)
  using true-clss-imp-true-cls-ext by (auto simp: true-annots-true-cls)
  then have lits-of-l (trail (fst T)) ⊨sextm clausesNOT (fst S)
  using rtrancpl-cdclNOT-restart-eq-sat-iff[of S T] full inv n-d unfolding full-def by blast
  moreover then have satisfiable (set-mset (clausesNOT (fst S)))
  using consistent-true-clss-ext-satisfiable distinct-consistent-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 = [] clausesNOT S = N and
    full: full cdclNOT-restart (S, 0) T and
    inv: inv S
  shows unsatisfiable (set-mset N)
    ∨ lits-of-l (trail (fst T)) ⊨sextm N ∧ 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

```

5.3 DPLL as an instance of NOT

5.3.1 DPLL with simple backtrack

We are using a concrete couple instead of an abstract state.

locale *dpll-with-backtrack*

begin

inductive *backtrack* :: ('v, unit) ann-lits × 'v clauses

⇒ ('v, unit) ann-lits × 'v clauses ⇒ bool **where**

backtrack-split (fst S) = (M', L # M) ⇒ is-decided L ⇒ D ∈# snd S

⇒ fst S ⊨_{as} CNot D ⇒ *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) ann-lits

assumes

backtrack: *backtrack* (M, N) (M', N') **and**

no-dup: (no-dup ∘ fst) (M, N) **and**

decomp: all-decomposition-implies-m N (get-all-ann-decomposition M)

shows

∃ C F' K F L l C'.

M = F' @ Decided K # F ∧

M' = Propagated L l # F ∧ N = N' ∧ C ∈# N ∧ F' @ Decided K # F ⊨_{as} CNot C ∧

undefined-lit F L ∧ atm-of L ∈ atms-of-mm N ∪ atm-of ' lits-of-l (F' @ Decided K # F) ∧

N ⊨_{pm} C' + {#L#} ∧ F ⊨_{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-decided L **and**

D ∈# snd ?S **and**

M ⊨_{as} CNot D **and**

bt: *backtrack* ?S (Propagated (− (lit-of L)) P # F, N) **and**

M': M' = Propagated (− (lit-of L)) P # F **and**

[simp]: N' = N

using *backtrackE*[OF *backtrack*] **by** (metis *backtrack* fstI sndI)

let ?K = lit-of L

let ?C = image-mset lit-of {#K ∈# mset M. is-decided K ∧ K ≠ L#} :: 'v clause

let ?C' = set-mset (image-mset single (?C + {#?K#}))

obtain K **where** L: L = Decided K **using** (is-decided L) **by** (cases L) auto

have M: M = F' @ Decided K # F

using *b-sp* **by** (metis L *backtrack-split-list-eq* fst-conv snd-conv)

moreover **have** F' @ Decided K # F ⊨_{as} CNot D

using (M ⊨_{as} CNot D) **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) ∈ atms-of-mm N ∪ atm-of ' lits-of-l (F' @ Decided K # F)

by auto

moreover

have set-mset N ∪ ?C' ⊨_{ps} {{#}}

proof −

have A: set-mset N ∪ ?C' ∪ unmark-l M =

set-mset N ∪ unmark-l M


```

    unfolding M L by auto
  have set-mset N  $\cup$   $\{\{\#lit-of L\# \} \mid L. is-decided L \wedge L \in set M\}$ 
     $\models_{ps} unmark-l M$ 
    using all-decomposition-implies-propagated-lits-are-implied[OF decomp] .
  moreover have C':  $?C' = \{\{\#lit-of L\# \} \mid L. is-decided L \wedge L \in set M\}$ 
    unfolding M L apply standard
    apply force
    using IntI by auto
  ultimately have N-C-M: set-mset N  $\cup$   $?C' \models_{ps} unmark-l M$ 
    by auto
  have set-mset N  $\cup$   $(\lambda L. \{\#lit-of L\# \}) ' (set M) \models_{ps} \{\{\#\}\}$ 
    unfolding true-clss-clss-def
  proof (intro allI impI, goal-cases)
    case (1 I) note tot = this(1) and cons = this(2) and I-N-M = this(3)
    have I  $\models D$ 
      using I-N-M  $\langle D \in \# \text{ snd } ?S \rangle$  unfolding true-clss-def by auto
    moreover have I  $\models_s CNot D$ 
      using  $\langle M \models_{as} CNot D \rangle$  unfolding M by (metis 1(3)  $\langle M \models_{as} CNot D \rangle$ 
        true-annots-true-clss true-clss-mono-set-mset-l true-clss-def
        true-clss-singleton-lit-of-implies-incl true-clss-union)
    ultimately show ?case using cons consistent-CNot-not by blast
  qed
  then show ?thesis
    using true-clss-clss-left-right[OF N-C-M, of  $\{\{\#\}\}$ ] unfolding A by auto
  qed
  have N  $\models_{pm} image-mset uminus ?C + \{\#-?K\# \}$ 
    unfolding true-clss-clss-def true-clss-clss-def total-over-m-def
  proof (intro allI impI)
    fix I
    assume
      tot: total-over-set I (atms-of-ms (set-mset N  $\cup$   $\{image-mset uminus ?C + \{\#-?K\# \}\}$ )) and
      cons: consistent-interp I and
      I  $\models_{sm} N$ 
    have  $(K \in I \wedge -K \notin I) \vee (-K \in I \wedge K \notin I)$ 
      using cons tot unfolding consistent-interp-def L by (cases K) auto
    have  $\{a \in set M. is-decided a \wedge a \neq Decided K\} =$ 
       $set M \cap \{L. is-decided L \wedge L \neq Decided K\}$ 
      by auto
    then have
      tI: total-over-set I (atm-of 'lit-of ' (set M  $\cap$   $\{L. is-decided L \wedge L \neq Decided K\}$ ))
      using tot by (auto simp add: L atms-of-uminus-lit-atm-of-lit-of)

  then have H:  $\bigwedge x.$ 
     $lit-of x \notin I \implies x \in set M \implies is-decided x$ 
     $\implies x \neq Decided K \implies -lit-of x \in I$ 
  proof -
    fix x :: ('v, unit) ann-lit
    assume a1:  $x \neq Decided K$ 
    assume a2:  $is-decided x$ 
    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  $\cap$   $\{m. is-decided m \wedge m \neq Decided K\}$ )
      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
  end

```

```

    then show  $\neg \text{lit-of } x \in I$ 
    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  $I \models \text{image-mset } \text{uminus } ?C + \{\#\neg \text{lit-of } L\#\}$ 
    unfolding true-clss-def true-clss-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  $F' \cap \{K. \text{is-decided } K \wedge K \neq L\} = \{\}$ 
    using backtrack-split-fst-not-decided[of - M] b-sp by auto
    then have  $F \models_{as} CNot (\text{image-mset } \text{uminus } ?C)$ 
    unfolding M CNot-def true-annots-def by (auto simp add: L lits-of-def)
    ultimately show ?thesis
    using M' (D  $\in \# \text{snd } ?S$ ) L by force
    qed

lemma backtrack-is-backjump':
  fixes M M' :: ('v, unit) ann-lits
  assumes
    backtrack: backtrack S T and
    no-dup: (no-dup  $\circ$  fst) S and
    decomp: all-decomposition-implies-m (snd S) (get-all-ann-decomposition (fst S))
  shows
     $\exists C F' K F L l C'.$ 
     $\text{fst } S = F' @ \text{Decided } K \# F \wedge$ 
     $T = (\text{Propagated } L l \# F, \text{snd } S) \wedge C \in \# \text{snd } S \wedge \text{fst } S \models_{as} CNot C$ 
     $\wedge \text{undefined-lit } F L \wedge \text{atm-of } L \in \text{atms-of-mm } (\text{snd } S) \cup \text{atm-of 'lits-of-l (fst } S) \wedge$ 
     $\text{snd } S \models_{pm} C' + \{\#L\#\} \wedge F \models_{as} CNot C'$ 
  apply (cases S, cases T)
  using backtrack-is-backjump[of fst S snd S fst T snd T] assms by fastforce

sublocale dp11-state
  fst snd  $\lambda L (M, N). (L \# M, N) \lambda (M, N). (tl M, N)$ 
   $\lambda C (M, N). (M, \{\#C\#\} + N) \lambda C (M, N). (M, \text{removeAll-mset } C N)$ 
  by unfold-locals (auto simp: ac-simps)

sublocale backjumping-ops
  fst snd  $\lambda L (M, N). (L \# M, N) \lambda (M, N). (tl M, N)$ 
   $\lambda C (M, N). (M, \{\#C\#\} + N) \lambda C (M, N). (M, \text{removeAll-mset } C N) \lambda - - S T. \text{backtrack } S T$ 
  by unfold-locals

thm reduce-trail-toNOT-clauses

lemma reduce-trail-toNOT:
  reduce-trail-toNOT F S =
    (if length (fst S)  $\geq$  length F
     then drop (length (fst S) - length F) (fst S)
     else [],
     snd S) (is ?R = ?C)
proof -
  have ?R = (fst ?R, snd ?R)

```

```

    by (cases reduce-trail-toNOT F S) auto
  also have (fst ?R, snd ?R) = ?C
    by (auto simp: trail-reduce-trail-toNOT-drop)
  finally show ?thesis .
qed

lemma backtrack-is-backjump'':
  fixes M M' :: ('v, unit) ann-lits
  assumes
    backtrack: backtrack S T and
    no-dup: (no-dup ∘ fst) S and
    decomp: all-decomposition-implies-m (snd S) (get-all-ann-decomposition (fst S))
  shows backjump S T
proof -
  obtain C F' K F L l C' where
    1: fst S = F' @ Decided K # F and
    2: T = (Propagated L l # F, snd S) and
    3: C ∈ # snd S and
    4: fst S ⊨as CNot C and
    5: undefined-lit F L and
    6: atm-of L ∈ atms-of-mm (snd S) ∪ atm-of ' lits-of-l (fst S) and
    7: snd S ⊨pm C' + {#L#} and
    8: F ⊨as CNot C'
  using backtrack-is-backjump'[OF assms] by force
  show ?thesis
  apply (cases S)
  using backjump.intros[OF 1 - - 4 5 - - 8, of T] 2 backtrack 1 5 3 6 7
  by (auto simp: state-eqNOT-def trail-reduce-trail-toNOT-drop
    reduce-trail-toNOT simp del: state-simpNOT)
qed

```

```

lemma can-do-bt-step:
  assumes
    M: fst S = F' @ Decided K # F and
    C ∈ # snd S and
    C: fst S ⊨as CNot C
  shows ¬ no-step backtrack S
proof -
  obtain L G' G where
    backtrack-split (fst S) = (G', L # G)
  unfolding M by (induction F' rule: ann-lit-list-induct) auto
  moreover then have is-decided L
    by (metis backtrack-split-snd-hd-decided list.distinct(1) list.sel(1) snd-conv)
  ultimately show ?thesis
    using backtrack.intros[of S G' L G C] (C ∈ # snd S) C unfolding M by auto
qed

```

end

```

sublocale dpll-with-backtrack ⊆ dpll-with-backjumping-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, removeAll-mset C N)
  λ(M, N). no-dup M ∧ all-decomposition-implies-m N (get-all-ann-decomposition M)
  λ- - - S T. backtrack S T
  λ- -. True
  apply unfold-locales

```

by (*metis* (*mono-tags*, *lifting*) *case-prod-beta comp-def dpll-with-backtrack.backtrack-is-backjump*''
dpll-with-backtrack.can-do-bt-step)

sublocale *dpll-with-backtrack* \subseteq *dpll-with-backjumping*

fst snd $\lambda L (M, N). (L \# M, N)$
 $\lambda(M, N). (tl\ M, N) \lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, removeAll-mset\ C\ N)$
 $\lambda(M, N). no-dup\ M \wedge all-decomposition-implies-m\ N\ (get-all-ann-decomposition\ M)$
 $\lambda- - S\ T. backtrack\ S\ T$
 $\lambda- -. True$
apply *unfold-locales*
using *dpll-bj-no-dup dpll-bj-all-decomposition-implies-inv* **apply** *fastforce*
done

context *dpll-with-backtrack*

begin

lemma *wf-tranclp-dpll-inital-state*:

assumes *fin*: *finite A*
shows *wf* $\{((M'::('v, unit)\ ann-lits, N'::'v\ clauses), ([], N)) | M'\ N'\ N.$
 $dpll-bj^{++}\ ([], N)\ (M', N') \wedge atms-of-mm\ N \subseteq atms-of-ms\ A\}$
using *wf-tranclp-dpll-bj[OF assms(1)]* **by** (*rule wf-subset*) *auto*

corollary *full-dpll-final-state-conclusive*:

fixes *M M' :: ('v, unit) ann-lits*
assumes
 $full: full\ dpll-bj\ ([], N)\ (M', N')$
shows *unsatisfiable* (*set-mset N*) $\vee (M' \models_{asm}\ N \wedge satisfiable\ (set-mset\ N))$
using *assms full-dpll-backjump-final-state[of ([],N) (M', N') set-mset N]* **by** *auto*

corollary *full-dpll-normal-form-from-init-state*:

fixes *M M' :: ('v, unit) ann-lits*
assumes
 $full: full\ dpll-bj\ ([], N)\ (M', N')$
shows $M' \models_{asm}\ N \longleftrightarrow satisfiable\ (set-mset\ N)$

proof –

have *no-dup M'*
using *rtranclp-dpll-bj-no-dup[of ([], N) (M', N')]*
 $full$ **unfolding** *full-def* **by** *auto*
then have $M' \models_{asm}\ N \implies satisfiable\ (set-mset\ N)$
using *distinct-consistent-interp satisfiable-carac' true-annots-true-cls* **by** *blast*
then show *?thesis*
using *full-dpll-final-state-conclusive[OF full]* **by** *auto*

qed

interpretation *conflict-driven-clause-learning-ops*

fst snd $\lambda L (M, N). (L \# M, N)$
 $\lambda(M, N). (tl\ M, N) \lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, removeAll-mset\ C\ N)$
 $\lambda(M, N). no-dup\ M \wedge all-decomposition-implies-m\ N\ (get-all-ann-decomposition\ M)$
 $\lambda- - S\ T. backtrack\ S\ T$
 $\lambda- -. True\ \lambda- -. False\ \lambda- -. False$
by *unfold-locales*

interpretation *conflict-driven-clause-learning*

fst snd $\lambda L (M, N). (L \# M, N)$
 $\lambda(M, N). (tl\ M, N) \lambda C (M, N). (M, \{\#C\# \} + N) \lambda C (M, N). (M, removeAll-mset\ C\ N)$
 $\lambda(M, N). no-dup\ M \wedge all-decomposition-implies-m\ N\ (get-all-ann-decomposition\ M)$
 $\lambda- - S\ T. backtrack\ S\ T$

$\lambda - . \text{ True } \lambda - . \text{ False } \lambda - . \text{ False}$
apply *unfold-locales*
using *cdcl_{NOT}-all-decomposition-implies cdcl_{NOT}-no-dup* **by** *fastforce*

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

5.3.2 Adding restarts

This was mainly a test whether it was possible to instantiate the assumption of the locale.

locale *dpll-withbacktrack-and-restarts* =
dpll-with-backtrack +
fixes $f :: nat \Rightarrow nat$
assumes *unbounded*: $unbounded f \text{ and } f\text{-}ge\text{-}1 : \bigwedge n. n \geq 1 \implies f n \geq 1$
begin
sublocale *cdcl_{NOT}-increasing-restarts*
 $fst\ snd\ \lambda L\ (M, N). (L \# M, N)\ \lambda (M, N). (tl\ M, N)$
 $\lambda C\ (M, N). (M, \{\#C\} + N)\ \lambda C\ (M, N). (M, removeAll\text{-}mset\ C\ N)\ f\ \lambda(-, N)\ S. S = ([], N)$
 $\lambda A\ (M, N). atms\text{-}of\text{-}mm\ N \subseteq atms\text{-}of\text{-}ms\ A \wedge atm\text{-}of\ ' lits\text{-}of\text{-}l\ M \subseteq atms\text{-}of\text{-}ms\ A \wedge finite\ A$
 $\wedge all\text{-}decomposition\text{-}implies\text{-}m\ N\ (get\text{-}all\text{-}ann\text{-}decomposition\ M)$
 $\lambda A\ T. (2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A))$
 $\quad -\ \mu_C\ (1 + card\ (atms\text{-}of\text{-}ms\ A))\ (2 + card\ (atms\text{-}of\text{-}ms\ A))\ (trail\text{-}weight\ T)\ dpll\text{-}bj$
 $\lambda (M, N). no\text{-}dup\ M \wedge all\text{-}decomposition\text{-}implies\text{-}m\ N\ (get\text{-}all\text{-}ann\text{-}decomposition\ M)$
 $\lambda A\ -. (2 + card\ (atms\text{-}of\text{-}ms\ A)) \wedge (1 + card\ (atms\text{-}of\text{-}ms\ A))$
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 id-apply 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

5.4 Weidenbach's DPLL

5.4.1 Rules

type-synonym $'a\ dpll_W\text{-}ann\text{-}lit = ('a, unit)\ ann\text{-}lit$
type-synonym $'a\ dpll_W\text{-}ann\text{-}lits = ('a, unit)\ ann\text{-}lits$

type-synonym $'v \text{ dpll}_W\text{-state} = 'v \text{ dpll}_W\text{-ann-lits} \times 'v \text{ clauses}$

abbreviation $\text{trail} :: 'v \text{ dpll}_W\text{-state} \Rightarrow 'v \text{ dpll}_W\text{-ann-lits}$ **where**
 $\text{trail} \equiv \text{fst}$

abbreviation $\text{clauses} :: 'v \text{ dpll}_W\text{-state} \Rightarrow 'v \text{ clauses}$ **where**
 $\text{clauses} \equiv \text{snd}$

inductive $\text{dpll}_W :: 'v \text{ dpll}_W\text{-state} \Rightarrow 'v \text{ dpll}_W\text{-state} \Rightarrow \text{bool}$ **where**
 $\text{propagate: } C + \{\#L\# \} \in \# \text{ clauses } S \Longrightarrow \text{trail } S \models_{\text{as}} \text{CNot } C \Longrightarrow \text{undefined-lit } (\text{trail } S) \ L$
 $\Longrightarrow \text{dpll}_W \ S \ (\text{Propagated } L \ () \ \# \ \text{trail } S, \text{ clauses } S) \mid$
 $\text{decided: } \text{undefined-lit } (\text{trail } S) \ L \Longrightarrow \text{atm-of } L \in \text{atms-of-mm } (\text{clauses } S)$
 $\Longrightarrow \text{dpll}_W \ S \ (\text{Decided } L \ \# \ \text{trail } S, \text{ clauses } S) \mid$
 $\text{backtrack: } \text{backtrack-split } (\text{trail } S) = (M', L \ \# \ M) \Longrightarrow \text{is-decided } L \Longrightarrow D \in \# \text{ clauses } S$
 $\Longrightarrow \text{trail } S \models_{\text{as}} \text{CNot } D \Longrightarrow \text{dpll}_W \ S \ (\text{Propagated } (- \ (\text{lit-of } L)) \ () \ \# \ M, \text{ clauses } S)$

5.4.2 Invariants

lemma $\text{dpll}_W\text{-distinct-inv:}$

assumes $\text{dpll}_W \ S \ S'$
and $\text{no-dup } (\text{trail } S)$
shows $\text{no-dup } (\text{trail } S')$
using assms

proof ($\text{induct rule: } \text{dpll}_W.\text{induct}$)

case ($\text{decided } L \ S$)

then show $?case$ **using** defined-lit-map **by force**

next

case ($\text{propagate } C \ L \ S$)

then show $?case$ **using** defined-lit-map **by force**

next

case ($\text{backtrack } S \ M' \ L \ M \ D$) **note** $\text{extracted} = \text{this}(1)$ **and** $\text{no-dup} = \text{this}(5)$

show $?case$

using $\text{no-dup backtrack-split-list-eq[of trail } S, \text{ symmetric}]$ **unfolding** extracted **by auto**

qed

lemma $\text{dpll}_W\text{-consistent-interp-inv:}$

assumes $\text{dpll}_W \ S \ S'$
and $\text{consistent-interp } (\text{lits-of-l } (\text{trail } S))$
and $\text{no-dup } (\text{trail } S)$
shows $\text{consistent-interp } (\text{lits-of-l } (\text{trail } S'))$
using assms

proof ($\text{induct rule: } \text{dpll}_W.\text{induct}$)

case ($\text{backtrack } S \ M' \ L \ M \ D$) **note** $\text{extracted} = \text{this}(1)$ **and** $\text{decided} = \text{this}(2)$ **and** $D = \text{this}(4)$ **and**
 $\text{cons} = \text{this}(5)$ **and** $\text{no-dup} = \text{this}(6)$

have $\text{no-dup}' : \text{no-dup } M$

by ($\text{metis } (\text{no-types}) \text{backtrack-split-list-eq distinct.simps}(2) \text{distinct-append extracted}$
 $\text{list.simps}(9) \text{map-append no-dup snd-conv}$)

then have $\text{insert } (\text{lit-of } L) \ (\text{lits-of-l } M) \subseteq \text{lits-of-l } (\text{trail } S)$

using $\text{backtrack-split-list-eq[of trail } S, \text{ symmetric}]$ **unfolding** extracted **by auto**

then have $\text{cons: consistent-interp } (\text{insert } (\text{lit-of } L) \ (\text{lits-of-l } M))$

using $\text{consistent-interp-subset cons}$ **by blast**

moreover

have $\text{lit-of } L \notin \text{lits-of-l } M$

using $\text{no-dup backtrack-split-list-eq[of trail } S, \text{ symmetric}]$ extracted
unfolding 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 *no-dup backtrack-split-list-eq*[of trail S , symmetric] **unfolding** *extracted by force*
 then have $\text{lit-of } L \notin \text{lits-of-l } M$
 unfolding *lits-of-def* **by force**
 ultimately show *?case* **by simp**
qed (*auto intro: consistent-add-undefined-lit-consistent*)

lemma *dpll_W-vars-in-snd-inv*:

assumes *dpll_W* $S S'$
 and *atm-of* ' (*lits-of-l* (trail S)) \subseteq *atms-of-mm* (*clauses* S)
 shows *atm-of* ' (*lits-of-l* (trail S')) \subseteq *atms-of-mm* (*clauses* S')
 using *assms*

proof (*induct rule: dpll_W.induct*)

case (*backtrack* $S M' L M D$)

then have *atm-of* (*lit-of* L) \in *atms-of-mm* (*clauses* S)
 using *backtrack-split-list-eq*[of trail S , symmetric] **by auto**

moreover

have *atm-of* ' *lits-of-l* (trail S) \subseteq *atms-of-mm* (*clauses* S)
 using *backtrack*(5) **by simp**

then have $\bigwedge x b. x b \in \text{set } M \implies \text{atm-of } (\text{lit-of } x b) \in \text{atms-of-mm } (\text{clauses } S)$
 using *backtrack-split-list-eq*[symmetric, of trail S] *backtrack.hyps*(1)

unfolding *lits-of-def* **by auto**

ultimately show *?case* **by** (*auto simp : lits-of-def*)

qed (*auto simp: in-plus-implies-atm-of-on-atms-of-ms*)

lemma *atms-of-ms-lit-of-atms-of*: *atms-of-ms* (($\lambda a. \{\# \text{lit-of } a \# \}$) ' c) = *atm-of* ' *lit-of* ' c

unfolding *atms-of-ms-def* **using** *image-iff* **by force**

theorem 2.8.2 page 73 of Weidenbach's book

lemma *dpll_W-propagate-is-conclusion*:

assumes *dpll_W* $S S'$

and *all-decomposition-implies-m* (*clauses* S) (*get-all-ann-decomposition* (trail S))

and *atm-of* ' *lits-of-l* (trail S) \subseteq *atms-of-mm* (*clauses* S)

shows *all-decomposition-implies-m* (*clauses* S') (*get-all-ann-decomposition* (trail S'))

using *assms*

proof (*induct rule: dpll_W.induct*)

case (*decided* $L S$)

then show *?case* **unfolding** *all-decomposition-implies-def* **by simp**

next

case (*propagate* $C L S$) **note** $\text{inS} = \text{this}(1)$ **and** $\text{cnot} = \text{this}(2)$ **and** $\text{IH} = \text{this}(4)$ **and** $\text{undef} = \text{this}(3)$ **and** $\text{atms-incl} = \text{this}(5)$

let $?I = \text{set } (\text{map } (\lambda a. \{\# \text{lit-of } a \# \}) (\text{trail } S)) \cup \text{set-mset } (\text{clauses } S)$

have $?I \models_p C + \{\# L \# \}$ **by** (*auto simp add: inS*)

moreover have $?I \models_{ps} \text{CNot } C$ **using** *true-annots-true-clss-cls cnot* **by fastforce**

ultimately have $?I \models_p \{\# L \# \}$ **using** *true-clss-cls-plus-CNot*[of $?I C L$] inS **by blast**

{

assume *get-all-ann-decomposition* (trail S) = []

then have *?case* **by blast**

}

moreover {

assume $n: \text{get-all-ann-decomposition } (\text{trail } S) \neq []$

have $1: \bigwedge a b. (a, b) \in \text{set } (\text{tl } (\text{get-all-ann-decomposition } (\text{trail } S)))$

$\implies (\text{unmark-l } a \cup \text{set-mset } (\text{clauses } S)) \models_{ps} \text{unmark-l } b$

using IH **unfolding** *all-decomposition-implies-def* **by** (*fastforce simp add: list.set-sel*(2) n)

moreover have $2: \bigwedge a c. \text{hd } (\text{get-all-ann-decomposition } (\text{trail } S)) = (a, c)$

$\implies (\text{unmark-l } a \cup \text{set-mset } (\text{clauses } S)) \models_{ps} (\text{unmark-l } c)$

by (*metis IH all-decomposition-implies-cons-pair all-decomposition-implies-single*)

```

    list.collapse n)
moreover have  $\exists: \bigwedge a\ c.\ hd\ (get\_all\_ann\_decomposition\ (trail\ S)) = (a,\ c)$ 
 $\implies (unmark-l\ a \cup set-mset\ (clauses\ S)) \models_p \{\#L\#$ 
proof -
  fix a c
  assume h:  $hd\ (get\_all\_ann\_decomposition\ (trail\ S)) = (a,\ c)$ 
  have h':  $trail\ S = c @ a$  using get-all-ann-decomposition-decomp h by blast
  have I:  $set\ (map\ (\lambda a.\ \{\#lit-of\ a\#\})\ a) \cup set-mset\ (clauses\ S)$ 
     $\cup unmark-l\ c \models_{ps}\ CNot\ C$ 
    using  $\langle ?I \models_{ps}\ CNot\ C \rangle$  unfolding h' by (simp add: Un-commute Un-left-commute)
  have
    atms-of-ms  $(CNot\ C) \subseteq atms-of-ms\ (set\ (map\ (\lambda a.\ \{\#lit-of\ a\#\})\ a) \cup set-mset\ (clauses\ S))$ 
    and
    atms-of-ms  $(unmark-l\ c) \subseteq atms-of-ms\ (set\ (map\ (\lambda a.\ \{\#lit-of\ a\#\})\ a)$ 
       $\cup set-mset\ (clauses\ S))$ 
    apply (metis CNot-plus Un-subset-iff atms-of-atms-of-ms-mono atms-of-ms-CNot-atms-of-
      atms-of-ms-union inS sup.coboundedI2)
    using inS atms-of-atms-of-ms-mono atms-incl by (fastforce simp: h')

  then have  $unmark-l\ a \cup set-mset\ (clauses\ S) \models_{ps}\ CNot\ C$ 
    using true-clss-clss-left-right[OF - I] h 2 by auto
  then show  $unmark-l\ a \cup set-mset\ (clauses\ S) \models_p \{\#L\#$ 
    by (metis (no-types) Un-insert-right inS insertI1 mk-disjoint-insert inS
      true-clss-clss-in true-clss-clss-plus-CNot)
qed
ultimately have ?case
  by (cases  $hd\ (get\_all\_ann\_decomposition\ (trail\ S))$ )
    (auto simp: all-decomposition-implies-def)
}
ultimately show ?case by auto
next
case (backtrack S M' L M D) note extracted = this(1) and decided = 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':  $\forall l \in set\ M'. \neg is-decided\ l$ 
  using extracted backtrack-split-fst-not-decided[of - trail S] by simp
have n:  $get\_all\_ann\_decomposition\ (trail\ S) \neq []$  by auto
then have all-decomposition-implies-m (clauses S)  $((L \# M,\ M')$ 
   $\# tl\ (get\_all\_ann\_decomposition\ (trail\ S)))$ 
  by (metis (no-types) IH extracted get-all-ann-decomposition-backtrack-split list.exhaust-sel)
then have 1:  $unmark-l\ (L \# M) \cup set-mset\ (clauses\ S) \models_{ps} (\lambda a.\ \{\#lit-of\ a\#\})\ 'set\ M'$ 
  by simp
moreover
  have  $unmark-l\ (L \# M) \cup unmark-l\ M' \models_{ps}\ CNot\ D$ 
    by (metis (mono-tags, lifting) S Un-commute cons image-Un set-append
      true-annots-true-clss-clss)
  then have 2:  $unmark-l\ (L \# M) \cup set-mset\ (clauses\ S) \cup unmark-l\ M'$ 
     $\models_{ps}\ CNot\ D$ 
    by (metis (no-types, lifting) Un-assoc Un-left-commute true-clss-clss-union-l-r)
ultimately
  have  $set\ (map\ (\lambda a.\ \{\#lit-of\ a\#\})\ (L \# M)) \cup set-mset\ (clauses\ S) \models_{ps}\ CNot\ D$ 
    using true-clss-clss-left-right by fastforce
  then have  $set\ (map\ (\lambda a.\ \{\#lit-of\ a\#\})\ (L \# M)) \cup set-mset\ (clauses\ S) \models_p \{\#\}$ 
    by (metis (mono-tags, lifting) D Un-def mem-Collect-eq
      true-clss-clss-contradiction-true-clss-clss-false)

```



```

then have IL: unmark-l  $M \cup \text{set-mset}(\text{clauses } S) \models_p \{\# - \text{lit-of } L\# \}$ 
  using true-clss-clss-false-left-right by auto
show ?case unfolding S all-decomposition-implies-def
proof
  fix x P level
  assume x:  $x \in \text{set}(\text{get-all-ann-decomposition}$ 
    ( $\text{fst}(\text{Propagated}(-\text{lit-of } L) P \# M, \text{clauses } S)))$ 
  let ?M' =  $\text{Propagated}(-\text{lit-of } L) P \# M$ 
  let ?hd =  $\text{hd}(\text{get-all-ann-decomposition } ?M')$ 
  let ?tl =  $\text{tl}(\text{get-all-ann-decomposition } ?M')$ 
  have x = ?hd  $\vee x \in \text{set } ?tl$ 
  using x
  by (cases  $\text{get-all-ann-decomposition } ?M'$ )
    auto
  moreover {
    assume x':  $x \in \text{set } ?tl$ 
    have L':  $\text{Decided}(\text{lit-of } L) = L$  using decided by (cases L, auto)
    have  $x \in \text{set}(\text{get-all-ann-decomposition } (M' @ L \# M))$ 
      using x' get-all-ann-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)  $\Rightarrow \text{unmark-l } Ls \cup \text{set-mset}(\text{clauses } S)$ 
       $\models_{ps} \text{unmark-l seen}$ 
      using decided IH by (cases L) (auto simp add: S all-decomposition-implies-def)
  }
  moreover {
    assume x':  $x = ?hd$ 
    have tl:  $\text{tl}(\text{get-all-ann-decomposition } (M' @ L \# M)) \neq []$ 
    proof -
      have f1:  $\bigwedge ms. \text{length}(\text{get-all-ann-decomposition } (M' @ ms))$ 
        =  $\text{length}(\text{get-all-ann-decomposition } ms)$ 
      by (simp add: M' get-all-ann-decomposition-remove-undecided-length)
      have Suc ( $\text{length}(\text{get-all-ann-decomposition } M)) \neq \text{Suc } 0$ 
      by blast
      then show ?thesis
        using f1 decided by (metis (no-types) get-all-ann-decomposition.simps(1) length-tl
          list.sel(3) list.size(3) ann-lit.collapse(1))
    qed
    obtain M0' M0 where
      L0:  $\text{hd}(\text{tl}(\text{get-all-ann-decomposition } (M' @ L \# M))) = (M0, M0')$ 
      by (cases  $\text{hd}(\text{tl}(\text{get-all-ann-decomposition } (M' @ L \# M)))$ )
    have x'':  $x = (M0, \text{Propagated}(-\text{lit-of } L) P \# M0')$ 
      unfolding x' using get-all-ann-decomposition-last-choice tl M' L0
      by (metis decided ann-lit.collapse(1))
    obtain l-get-all-ann-decomposition where
       $\text{get-all-ann-decomposition}(\text{trail } S) = (L \# M, M') \# (M0, M0') \#$ 
       $l\text{-get-all-ann-decomposition}$ 
      using get-all-ann-decomposition-backtrack-split extracted by (metis (no-types) L0 S
        hd-Cons-tl n tl)
    then have  $M = M0' @ M0$  using get-all-ann-decomposition-hd-hd by fastforce
    then have IL':  $\text{unmark-l } M0 \cup \text{set-mset}(\text{clauses } S)$ 
       $\cup \text{unmark-l } M0' \models_{ps} \{\# - \text{lit-of } L\# \}$ 
      using IL by (simp add: Un-commute Un-left-commute image-Un)
    moreover have H:  $\text{unmark-l } M0 \cup \text{set-mset}(\text{clauses } S)$ 
       $\models_{ps} \text{unmark-l } M0'$ 
      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 $(Ls, seen) \Rightarrow unmark-l\ Ls \cup set-mset\ (clauses\ S)$
 $\models_{ps} unmark-l\ seen$
 using *true-clss-clss-left-right unfolding* x'' by *auto*
 }
 ultimately show case x of $(Ls, seen) \Rightarrow$
 $unmark-l\ Ls \cup set-mset\ (snd\ (?M', clauses\ S))$
 $\models_{ps} unmark-l\ seen$
 unfolding *snd-conv* by *blast*
 qed
 qed

theorem 2.8.3 page 73 of Weidenbach's book

theorem *dpll_W-propagate-is-conclusion-of-decided*:
 assumes *dpll_W S S'*
 and *all-decomposition-implies-m (clauses S) (get-all-ann-decomposition (trail S))*
 and *atm-of ' lits-of-l (trail S) \subseteq atms-of-mm (clauses S)*
 shows *set-mset (clauses S') \cup { {#lit-of L#} | L. is-decided L \wedge L \in set (trail S') }*
 $\models_{ps} (\lambda a. \{ \#lit-of\ a\# \})\ ' \bigcup (set\ ' \text{snd}\ ' set\ (get-all-ann-decomposition\ (trail\ S')))$
 using *all-decomposition-implies-trail-is-implied*[*OF dpll_W-propagate-is-conclusion*[*OF assms*]] .

theorem 2.8.4 page 73 of Weidenbach's book

lemma *only-propagated-vars-unsat*:
 assumes *decided: $\forall x \in set\ M. \neg is-decided\ x$*
 and *DN: $D \in N$ and $D: M \models_{as} CNot\ D$*
 and *inv: all-decomposition-implies N (get-all-ann-decomposition M)*
 and *atm-incl: atm-of ' lits-of-l 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-decided L \wedge L \in set M } = { }* using *decided* by *auto*
 have *atms-of-ms (N \cup unmark-l 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 ($\lambda a. \{ \#lit-of\ a\# \})\ ' (set\ M))$*
 using *tot unfolding total-over-m-def* by *auto*
 then have $I \models_s (\lambda a. \{ \#lit-of\ a\# \})\ ' (set\ M)$
 using *all-decomposition-implies-propagated-lits-are-implied*[*OF inv*] *cons I*
 unfolding *true-clss-clss-def l0* by *auto*
 then have *IM: $I \models_s unmark-l\ M$* by *auto*
 {
 fix *K*
 assume $K \in \# D$
 then have $-K \in lits-of-l\ M$
 by (*auto split: if-split-asm*
 intro: allE[*OF D*[*unfolded true-annots-def Ball-def*], of { $\#-K\#$ }])
 then have $-K \in I$ using *IM true-clss-singleton-lit-of-implies-incl* by *fastforce*
 }
 then have $\neg I \models D$ using *cons unfolding true-clss-def consistent-interp-def* by *auto*

then show *False* **using** *I-D* **by** *blast*
qed

lemma *dp_{ll}_W-same-clauses*:

assumes *dp_{ll}_W S S'*

shows *clauses S = clauses S'*

using *assms* **by** (*induct rule: dp_{ll}_W.induct, auto*)

lemma *rtranc_lp-dp_{ll}_W-inv*:

assumes *rtranc_lp dp_{ll}_W S S'*

and *inv*: *all-decomposition-implies-m (clauses S) (get-all-ann-decomposition (trail S))*

and *atm-incl*: *atm-of ' lits-of-l (trail S) \subseteq atms-of-mm (clauses S)*

and *consistent-interp (lits-of-l (trail S))*

and *no-dup (trail S)*

shows *all-decomposition-implies-m (clauses S') (get-all-ann-decomposition (trail S'))*

and *atm-of ' lits-of-l (trail S') \subseteq atms-of-mm (clauses S')*

and *clauses S = clauses S'*

and *consistent-interp (lits-of-l (trail S'))*

and *no-dup (trail S')*

using *assms*

proof (*induct rule: rtranc_lp-induct*)

case *base*

show

all-decomposition-implies-m (clauses S) (get-all-ann-decomposition (trail S)) **and**

atm-of ' lits-of-l (trail S) \subseteq atms-of-mm (clauses S) **and**

clauses S = clauses S **and**

consistent-interp (lits-of-l (trail S)) **and**

no-dup (trail S) **using** *assms* **by** *auto*

next

case (*step S' S''*) **note** *dp_{ll}_WStar = this(1)* **and** *IH = this(3,4,5,6,7)* **and**

dp_{ll}_W = this(2)

moreover

assume

inv: *all-decomposition-implies-m (clauses S) (get-all-ann-decomposition (trail S))* **and**

atm-incl: *atm-of ' lits-of-l (trail S) \subseteq atms-of-mm (clauses S)* **and**

cons: *consistent-interp (lits-of-l (trail S))* **and**

no-dup (trail S)

ultimately have *decomp*: *all-decomposition-implies-m (clauses S')*

(get-all-ann-decomposition (trail S')) **and**

atm-incl': *atm-of ' lits-of-l (trail S') \subseteq atms-of-mm (clauses S')* **and**

snd: *clauses S = clauses S'* **and**

cons': *consistent-interp (lits-of-l (trail S'))* **and**

no-dup': *no-dup (trail S')* **by** *blast+*

show *clauses S = clauses S''* **using** *dp_{ll}_W-same-clauses[OF dp_{ll}_W] snd* **by** *metis*

show *all-decomposition-implies-m (clauses S'') (get-all-ann-decomposition (trail S''))*

using *dp_{ll}_W-propagate-is-conclusion[OF dp_{ll}_W] decomp atm-incl'* **by** *auto*

show *atm-of ' lits-of-l (trail S'') \subseteq atms-of-mm (clauses S'')*

using *dp_{ll}_W-vars-in-snd-inv[OF dp_{ll}_W] atm-incl atm-incl'* **by** *auto*

show *no-dup (trail S'')* **using** *dp_{ll}_W-distinct-inv[OF dp_{ll}_W] no-dup' dp_{ll}_W* **by** *auto*

show *consistent-interp (lits-of-l (trail S''))*

using *cons' no-dup' dp_{ll}_W-consistent-interp-inv[OF dp_{ll}_W]* **by** *auto*

qed

definition *dp_{ll}_W-all-inv S* \equiv

(all-decomposition-implies-m (clauses S) (get-all-ann-decomposition (trail S)))

$\wedge \text{atm-of } \text{' lits-of-l (trail S) } \subseteq \text{atms-of-mm (clauses S)}$
 $\wedge \text{consistent-interp (lits-of-l (trail S))}$
 $\wedge \text{no-dup (trail S)}$

lemma *dpll_W-all-inv-dest*[*dest*]:
assumes *dpll_W-all-inv S*
shows *all-decomposition-implies-m (clauses S) (get-all-ann-decomposition (trail S))*
and *atm-of ' lits-of-l (trail S) \subseteq atms-of-mm (clauses S)*
and *consistent-interp (lits-of-l (trail S)) \wedge no-dup (trail S)*
using *assms unfolding dpll_W-all-inv-def lits-of-def* **by** *auto*

lemma *rtrancpl-dpll_W-all-inv*:
assumes *rtrancpl dpll_W S S'*
and *dpll_W-all-inv S*
shows *dpll_W-all-inv S'*
using *assms rtrancpl-dpll_W-inv[OF assms(1)] unfolding dpll_W-all-inv-def lits-of-def* **by** *blast*

lemma *dpll_W-all-inv*:
assumes *dpll_W S S'*
and *dpll_W-all-inv S*
shows *dpll_W-all-inv S'*
using *assms rtrancpl-dpll_W-all-inv* **by** *blast*

lemma *rtrancpl-dpll_W-inv-starting-from-0*:
assumes *rtrancpl dpll_W S S'*
and *inv: trail S = []*
shows *dpll_W-all-inv S'*
proof –
have *dpll_W-all-inv S*
using *assms unfolding all-decomposition-implies-def dpll_W-all-inv-def* **by** *auto*
then show *?thesis using rtrancpl-dpll_W-all-inv[OF assms(1)]* **by** *blast*
qed

lemma *dpll_W-can-do-step*:
assumes *consistent-interp (set M)*
and *distinct M*
and *atm-of ' (set M) \subseteq atms-of-mm N*
shows *rtrancpl dpll_W ([], N) (map Decided M, N)*
using *assms*
proof (*induct M*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons L M*)
then have *undefined-lit (map Decided M) L*
unfolding *defined-lit-def consistent-interp-def* **by** *auto*
moreover have *atm-of L \in atms-of-mm N* **using** *Cons.prem(3)* **by** *auto*
ultimately have *dpll_W (map Decided M, N) (map Decided (L # M), N)*
using *dpll_W.decided* **by** *auto*
moreover have *consistent-interp (set M)* **and** *distinct M* **and** *atm-of ' set M \subseteq atms-of-mm N*
using *Cons.prem* **unfolding** *consistent-interp-def* **by** *auto*
ultimately show *?case using Cons.hyps* **by** *auto*
qed

definition *conclusive-dpll_W-state* (*S:: 'v dpll_W-state*) \longleftrightarrow
(trail S \models asm clauses S \vee ($\forall L \in \text{set (trail S). } \neg \text{is-decided } L$))

$\wedge (\exists C \in \# \text{ clauses } S. \text{ trail } S \models_{as} C \text{Not } C)))$

theorem 2.8.6 page 74 of Weidenbach's book

lemma *dpll_W-strong-completeness*:

assumes *set* $M \models_{sm} N$

and *consistent-interp* (*set* M)

and *distinct* M

and *atm-of* ' (*set* M) \subseteq *atms-of-mm* N

shows $dpll_W^{**} ([], N) (\text{map } Decided\ M, N)$

and *conclusive-dpll_W-state* (*map* *Decided* M, N)

proof –

show *rtrancpl* $dpll_W ([], N) (\text{map } Decided\ M, N)$ **using** *dpll_W-can-do-step* *assms* **by** *auto*

have *map* *Decided* $M \models_{asm} N$ **using** *assms*(1) *true-annots-decided-true-cls* **by** *auto*

then show *conclusive-dpll_W-state* (*map* *Decided* M, N)

unfolding *conclusive-dpll_W-state-def* **by** *auto*

qed

theorem 2.8.5 page 73 of Weidenbach's book

lemma *dpll_W-sound*:

assumes

rtrancpl $dpll_W ([], N) (M, N)$ **and**

$\forall S. \neg dpll_W (M, N) S$

shows $M \models_{asm} N \longleftrightarrow \text{satisfiable } (\text{set-mset } N) (\text{is } ?A \longleftrightarrow ?B)$

proof

let $?M' = \text{lits-of-l } M$

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 $(\exists L. \text{undefined-lit } M\ L \wedge \text{atm-of } L \in \text{atms-of-mm } N) \vee (\exists D \in \# N. M \models_{as} C \text{Not } D)$

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-decided-or-true-lit* *true-cls-def* **by** *blast*

then show *?thesis*

by (*metis* *Bex-def* *D* *atms-of-atms-of-ms-mono* *rev-subsetD*)

qed

moreover {

assume $\exists L. \text{undefined-lit } M\ L \wedge \text{atm-of } L \in \text{atms-of-mm } N$

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 $\forall l \in \text{set } M. \neg \text{is-decided } l$

moreover have *dpll_W-all-inv* ($[], N$)

using *assms* **unfolding** *all-decomposition-implies-def* *dpll_W-all-inv-def* **by** *auto*

```

ultimately have unsatisfiable (set-mset N)
  using only-propagated-vars-unsat[of M D set-mset N] DN MD
  rtranchp-dpllW-all-inv[OF assms(1)] by force
then have False using ⟨?B⟩ by blast
}
moreover {
  assume l: ∃ l ∈ set M. is-decided l
  then have False
    using backtrack[of (M, N) - - D ] DN MD assms(2)
    backtrack-split-some-is-decided-then-snd-has-hd[OF l]
    by (metis backtrack-split-snd-hd-decided fst-conv list.distinct(1) list.sel(1) snd-conv)
  }
ultimately have False by blast
}
ultimately show False by blast
qed
qed

```

5.4.3 Termination

definition $dpll_W\text{-mes } M \ n =$
 $\text{map } (\lambda l. \text{if is-decided } l \text{ then } 2 \text{ else } (1::\text{nat})) (\text{rev } M) \ @ \ \text{replicate } (n - \text{length } M) \ 3$

lemma $\text{length-dpll}_W\text{-mes}$:
assumes $\text{length } M \leq n$
shows $\text{length } (dpll_W\text{-mes } M \ n) = n$
using *assms* **unfolding** $dpll_W\text{-mes-def}$ **by** *auto*

lemma $\text{distinctcard-atm-of-lit-of-eq-length}$:
assumes $\text{no-dup } S$
shows $\text{card } (\text{atm-of } \text{'lits-of-lit } S) = \text{length } S$
using *assms* **by** (*induct* S) (*auto simp add: image-image lits-of-def*)

lemma $dpll_W\text{-card-decrease}$:
assumes $dpll$: $dpll_W \ S \ S'$ **and** $\text{length } (\text{trail } S') \leq \text{card vars}$
and $\text{length } (\text{trail } S) \leq \text{card vars}$
shows $(dpll_W\text{-mes } (\text{trail } S') \ (\text{card vars}), dpll_W\text{-mes } (\text{trail } S) \ (\text{card vars}))$
 $\in \text{lexn } \{(a, b). a < b\} \ (\text{card vars})$
using *assms*

proof (*induct rule: dpll_W.induct*)
case (*propagate C L S*)
have m : $\text{map } (\lambda l. \text{if is-decided } l \text{ then } 2 \text{ else } 1) (\text{rev } (\text{trail } S))$
 $\ @ \ \text{replicate } (\text{card vars} - \text{length } (\text{trail } S)) \ 3$
 $= \text{map } (\lambda l. \text{if is-decided } l \text{ then } 2 \text{ else } 1) (\text{rev } (\text{trail } S)) \ @ \ 3$
 $\ # \ \text{replicate } (\text{card vars} - \text{Suc } (\text{length } (\text{trail } S))) \ 3$
using *propagate.prem[simplified]* **using** *Suc-diff-le* **by** *fastforce*
then show *?case*
using *propagate.prem(1)* **unfolding** $dpll_W\text{-mes-def}$ **by** (*fastforce simp add: lexn-conv assms(2)*)

next

case (*decided S L*)
have m : $\text{map } (\lambda l. \text{if is-decided } l \text{ then } 2 \text{ else } 1) (\text{rev } (\text{trail } S))$
 $\ @ \ \text{replicate } (\text{card vars} - \text{length } (\text{trail } S)) \ 3$
 $= \text{map } (\lambda l. \text{if is-decided } l \text{ then } 2 \text{ else } 1) (\text{rev } (\text{trail } S)) \ @ \ 3$
 $\ # \ \text{replicate } (\text{card vars} - \text{Suc } (\text{length } (\text{trail } S))) \ 3$
using *decided.prem[simplified]* **using** *Suc-diff-le* **by** *fastforce*
then show *?case*

using *decided.premis* **unfolding** *dpll_W-mes-def* **by** (*force simp add: lexn-conv assms(2)*)
 next
 case (*backtrack S M' L M D*)
 have *L: is-decided 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** *dpll_W-mes-def S* **by** (*fastforce simp add: lexn-conv assms(2)*)
 qed

theorem 2.8.7 page 74 of Weidenbach's book

lemma *dpll_W-card-decrease'*:

assumes *dpll: dpll_W S S'*
 and *atm-incl: atm-of ' lits-of-l (trail S) ⊆ atms-of-mm (clauses S)*
 and *no-dup: no-dup (trail S)*
 shows (*dpll_W-mes (trail S') (card (atms-of-mm (clauses S')))*),
 (*dpll_W-mes (trail S) (card (atms-of-mm (clauses S)))*) ∈ *lex {(a, b). a < b}*

proof –

have *finite (atms-of-mm (clauses S))* **unfolding** *atms-of-ms-def* **by** *auto*
 then have *1: length (trail S) ≤ card (atms-of-mm (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 dpll_W-distinct-inv no-dup* **by** *blast*
 have *SS': clauses S' = clauses S* **using** *dpll* **by** (*auto dest!: dpll_W-same-clauses*)
 have *atm-incl': atm-of ' lits-of-l (trail S') ⊆ atms-of-mm (clauses S')*
 using *atm-incl dpll dpll_W-vars-in-snd-inv[OF dpll]* **by** *force*
 have *finite (atms-of-mm (clauses S'))*
 unfolding *atms-of-ms-def* **by** *auto*
 then have *2: length (trail S') ≤ card (atms-of-mm (clauses S'))*
 using *distinctcard-atm-of-lit-of-eq-length[OF no-dup'] atm-incl' card-mono SS'* **by** *metis*

ultimately have (*dpll_W-mes (trail S') (card (atms-of-mm (clauses S)))*),
 (*dpll_W-mes (trail S) (card (atms-of-mm (clauses S)))*)
 ∈ *lexn {(a, b). a < b} (card (atms-of-mm (clauses S)))*
 using *dpll_W-card-decrease[OF assms(1), of atms-of-mm (clauses S)]* **by** *blast*
 then have (*dpll_W-mes (trail S') (card (atms-of-mm (clauses S)))*),
 (*dpll_W-mes (trail S) (card (atms-of-mm (clauses S)))*) ∈ *lex {(a, b). a < b}*
 unfolding *lex-def* **by** *auto*
 then show (*dpll_W-mes (trail S') (card (atms-of-mm (clauses S')))*),
 (*dpll_W-mes (trail S) (card (atms-of-mm (clauses S)))*) ∈ *lex {(a, b). a < b}*
 using *dpll_W-same-clauses[OF assms(1)]* **by** *auto*

qed

lemma *wf-lexn: wf (lexn {(a, b). (a::nat) < b} (card (atms-of-mm (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-all-inv S ∧ dpll_W S S'}
apply (*rule wf-wf-if-measure'[OF wf-lex-less, of - -*
 λS. dpll_W-mes (trail S) (card (atms-of-mm (clauses S)))])
using *dpll_W-card-decrease'* **by** *fast*

lemma *dpll_W-trancp-star-commute*:
 $\{(S', S). \text{dpll}_W\text{-all-inv } S \wedge \text{dpll}_W S S'\}^+ = \{(S', S). \text{dpll}_W\text{-all-inv } S \wedge \text{trancp dpll}_W S S'\}$
 (is ?A = ?B)
proof
 { fix S S'
 assume (S, S') ∈ ?A
 then have (S, S') ∈ ?B
 by (induct rule: tranc1.induct, auto)
 }
 then show ?A ⊆ ?B by blast
 { fix S S'
 assume (S, S') ∈ ?B
 then have dpll_W⁺⁺ S' S and dpll_W-all-inv S' by auto
 then have (S, S') ∈ ?A
 proof (induct rule: trancp.induct)
 case r-into-tranc1
 then show ?case by (simp-all add: r-into-tranc1')
 next
 case (tranc1-into-tranc1 S S' S'')
 then have (S', S) ∈ {a. case a of (S', S) ⇒ dpll_W-all-inv S ∧ dpll_W S S'}⁺ by blast
 moreover have dpll_W-all-inv S'
 using rtrancp-dpll_W-all-inv[OF trancp-into-rtrancp[OF tranc1-into-tranc1.hyps(1)]]
 tranc1-into-tranc1.prem by auto
 ultimately have (S'', S') ∈ {(pa, p). dpll_W-all-inv p ∧ dpll_W p pa}⁺
 using ⟨dpll_W-all-inv S'⟩ tranc1-into-tranc1.hyps(3) by blast
 then show ?case
 using ⟨(S', S) ∈ {a. case a of (S', S) ⇒ dpll_W-all-inv S ∧ dpll_W S S'}⁺⟩ by auto
 qed
 }
 then show ?B ⊆ ?A by blast
qed

lemma *dpll_W-wf-trancp*: wf {(S', S). dpll_W-all-inv S ∧ dpll_W⁺⁺ S S'}
 unfolding dpll_W-trancp-star-commute[symmetric] by (simp add: dpll_W-wf wf-tranc1)

lemma *dpll_W-wf-plus*:
 wf {(S', ([], N)) | S'. dpll_W⁺⁺ ([], N) S'} (is wf ?P)
 apply (rule wf-subset[OF dpll_W-wf-trancp, of ?P])
 unfolding dpll_W-all-inv-def by auto

5.4.4 Final States

Proposition 2.8.1: final states are the normal forms of dpll_W

lemma *dpll_W-no-more-step-is-a-conclusive-state*:

assumes $\forall S'. \neg \text{dpll}_W S S'$
 shows conclusive-dpll_W-state S

proof —

have vars: $\forall s \in \text{atms-of-mm } (\text{clauses } S). s \in \text{atm-of ' lits-of-l } (\text{trail } S)$
proof (rule ccontr)
 assume $\neg (\forall s \in \text{atms-of-mm } (\text{clauses } S). s \in \text{atm-of ' lits-of-l } (\text{trail } S))$
 then obtain L where
 L-in-atms: $L \in \text{atms-of-mm } (\text{clauses } S)$ and
 L-notin-trail: $L \notin \text{atm-of ' lits-of-l } (\text{trail } S)$ bymetis
 obtain L' where L': $\text{atm-of } L' = L$ by (meson literal.sel(2))


```

then have undefined-lit (trail S) L'
  unfolding Decided-Propagated-in-iff-in-lits-of-l by (metis L-notin-trail atm-of-uminus imageI)
then show False using dpllW.decided assms(1) L-in-atms L' by blast
qed
show ?thesis
proof (rule ccontr)
  assume not-final:  $\neg$  ?thesis
  then have
     $\neg$  trail S  $\models_{asm}$  clauses S and
     $(\exists L \in set (trail S). is-decided L) \vee (\forall C \in \# clauses S. \neg trail S \models_{as} CNot C)$ 
  unfolding conclusive-dpllW-state-def by auto
  moreover {
    assume  $\exists L \in set (trail S). is-decided L$ 
    then obtain L M' M where L: backtrack-split (trail S) = (M', L # M)
      using backtrack-split-some-is-decided-then-snd-has-hd by blast
    obtain D where D  $\in \# clauses S$  and  $\neg trail S \models_a D$ 
      using  $\langle \neg trail S \models_{asm} clauses S \rangle$  unfolding true-annots-def by auto
    then have  $\forall s \in atms-of-ms \{D\}. s \in atm-of \text{ 'lits-of-l (trail S) }$ 
      using vars unfolding atms-of-ms-def by auto
    then have trail S  $\models_{as} CNot D$ 
      using all-variables-defined-not-imply-cnot[of D]  $\langle \neg trail S \models_a D \rangle$  by auto
    moreover have is-decided L
      using L by (metis backtrack-split-snd-hd-decided list.distinct(1) list.sel(1) snd-conv)
    ultimately have False
      using assms(1) dpllW.backtrack L  $\langle D \in \# clauses S \rangle \langle trail S \models_{as} CNot D \rangle$  by blast
  }
  moreover {
    assume tr:  $\forall C \in \# clauses S. \neg trail S \models_{as} CNot C$ 
    obtain C where C-in-cl: C  $\in \# clauses S$  and trC:  $\neg trail S \models_a C$ 
      using  $\langle \neg trail S \models_{asm} clauses S \rangle$  unfolding true-annots-def by auto
    have  $\forall s \in atms-of-ms \{C\}. s \in atm-of \text{ 'lits-of-l (trail S) }$ 
      using vars  $\langle C \in \# clauses S \rangle$  unfolding atms-of-ms-def by auto
    then have trail S  $\models_{as} CNot C$ 
      by (meson C-in-cl tr trC all-variables-defined-not-imply-cnot)
    then have False using tr C-in-cl by auto
  }
  ultimately show False by blast
qed
qed

```

```

lemma dpllW-conclusive-state-correct:
  assumes dpllW** ([], N) (M, N) and conclusive-dpllW-state (M, N)
  shows M  $\models_{asm} N \longleftrightarrow$  satisfiable (set-mset N) (is ?A  $\longleftrightarrow$  ?B)
proof
  let ?M' = lits-of-l M
  assume ?A
  then have ?M'  $\models_{sm} N$  by (simp add: true-annots-true-cl)
  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:  $\forall L \in set M. \neg is-decided L \ \exists C \in \# N. M \models_{as} CNot C$ 

```

```

    using  $n$  assms(2) unfolding conclusive-dpllW-state-def by auto
    moreover obtain  $D$  where  $DN$ :  $D \in \# N$  and  $MD$ :  $M \models_{as} CNot D$  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  $\langle ?B \rangle$  by blast
  qed
qed

```

5.4.5 Link with NOT's DPLL

interpretation *dpll_W-NOT*: *dpll-with-backtrack* .

```

declare dpllW-NOT.state-simpNOT[simp del]
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
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)
    apply (rule dpllW-NOT.bj-propagateNOT)
    apply (rule dpllW-NOT.propagateNOT.propagateNOT; simp?)
    apply fastforce
    apply (rule dpllW-NOT.bj-decideNOT)
    apply (rule dpllW-NOT.decideNOT.decideNOT; simp?)
    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.decideNOTE, cases S)
    apply (frule decided; simp)

    apply (elim dpllW-NOT.propagateNOTE, cases S)
    apply (auto intro!: propagate[of - - (-, -), simplified])[]
    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 dpllW**  $S T$ 

```

```

using assms apply (induction)
apply simp
by (auto intro: dpllW-bj-dpll rtranclp.rtrancl-into-rtrancl rtranclp-dpllW-all-inv)

lemma dpll-conclusive-state-correctness:
  assumes dpllW-NOT.dpll-bj** ([], N) (M, N) and conclusive-dpllW-state (M, N)
  shows M ⊨asm N ⟷ satisfiable (set-mset N)
proof -
  have dpllW-all-inv ([], N)
  unfolding dpllW-all-inv-def by auto
  show ?thesis
  apply (rule dpllW-conclusive-state-correct)
  apply (simp add: ⟨dpllW-all-inv ([], N)⟩ assms(1) rtranclp-dpll-rtranclp-dpllW)
  using assms(2) by simp
qed

end
theory CDCL-W-Level
imports Partial-Annotated-Clausal-Logic
begin

```

Level of literals and clauses

Getting the level of a variable, implies that the list has to be reversed. Here is the function after reversing.

abbreviation *count-decided* :: ('v, 'm) ann-lits ⇒ nat **where**
count-decided l ≡ length (filter is-decided l)

abbreviation *get-level* :: ('v, 'm) ann-lits ⇒ 'v literal ⇒ nat **where**
get-level S L ≡ length (filter is-decided (dropWhile (λS. atm-of (lit-of S) ≠ atm-of L) S))

lemma *get-level-uminus*: *get-level* M (−L) = *get-level* M L
 by auto

lemma *atm-of-notin-get-rev-level-eq-0*[simp]:
 assumes atm-of L ∉ atm-of ' lits-of-l M
 shows *get-level* M L = 0
 using assms by (induct M rule: ann-lit-list-induct) auto

lemma *get-level-ge-0-atm-of-in*:
 assumes *get-level* M L > n
 shows atm-of L ∈ atm-of ' lits-of-l M
 using assms by (induct M arbitrary: n rule: ann-lit-list-induct) fastforce+

In *get-level* (resp. *get-level*), the beginning (resp. the end) can be skipped if the literal is not in the beginning (resp. the end).

lemma *get-rev-level-skip*[simp]:
 assumes atm-of L ∉ atm-of ' lits-of-l M
 shows *get-level* (M @ M') L = *get-level* M' L
 using assms by (induct M rule: ann-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 atm-of L ∈ atm-of ' lits-of-l M

shows $\text{get-level } (M @ M') L = \text{get-level } M L + \text{length } (\text{filter is-decided } M')$
using *assms* **by** (*induct* M' *rule*: *ann-lit-list-induct*) (*auto simp*: *lits-of-def*)

lemma *get-level-skip-beginning*:
assumes $\text{atm-of } L' \neq \text{atm-of } (\text{lit-of } K)$
shows $\text{get-level } (K \# M) L' = \text{get-level } M L'$
using *assms* **by** *auto*

lemma *get-level-skip-beginning-not-decided*[*simp*]:
assumes $\text{atm-of } L \notin \text{atm-of ' lits-of-l } S$
and $\forall s \in \text{set } S. \neg \text{is-decided } s$
shows $\text{get-level } (M @ S) L = \text{get-level } M L$
using *assms* **apply** (*induction* S *rule*: *ann-lit-list-induct*)
apply *auto*[2]
apply (*case-tac* $\text{atm-of } L \in \text{atm-of ' lits-of-l } M$)
apply (*auto simp*: *image-iff lits-of-def filter-empty-conv dest*: *set-dropWhileD*)
done

lemma *get-level-skip-in-all-not-decided*:
fixes $M :: ('a, 'b) \text{ ann-lits}$ **and** $L :: 'a \text{ literal}$
assumes $\forall m \in \text{set } M. \neg \text{is-decided } m$
and $\text{atm-of } L \in \text{atm-of ' lits-of-l } M$
shows $\text{get-level } M L = 0$
using *assms* **by** (*induction* M *rule*: *ann-lit-list-induct*) *auto*

lemma *get-level-skip-all-not-decided*[*simp*]:
fixes M
assumes $\forall m \in \text{set } M. \neg \text{is-decided } m$
shows $\text{get-level } M L = 0$
using *assms* **by** (*auto simp*: *filter-empty-conv dest*: *set-dropWhileD*)

abbreviation $M\text{Max } M \equiv \text{Max } (\text{set-mset } M)$

the $\{\#0 :: 'a\# \}$ is there to ensure that the set is not empty.

definition *get-maximum-level* :: $('a, 'b) \text{ ann-lits} \Rightarrow 'a \text{ literal multiset} \Rightarrow \text{nat}$
where
 $\text{get-maximum-level } M D = M\text{Max } (\{\#0\# \} + \text{image-mset } (\text{get-level } M) D)$

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]:
get-maximum-level $M \{ \#L\# \} = \text{get-level } M L$
unfolding *get-maximum-level-def* **by** *simp*

lemma *get-maximum-level-plus*:
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*: *get-maximum-level* $M D = n$
shows $\exists L \in \#D. \text{get-level } M L = n$

proof –
have $f: \text{finite } (\text{insert } 0 ((\lambda L. \text{get-level } M L) \text{ ` set-mset } D))$ **by** *auto*
then have $n \in ((\lambda L. \text{get-level } M L) \text{ ` set-mset } D)$
using $n \text{ max Max-in}[OF f]$ **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* $L \notin \text{atms-of } D$
shows *get-maximum-level* $(\text{Propagated } L C \# M) D = \text{get-maximum-level } M D$
using *assms* **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 ann-lit.sel*(2)
multiset.map-cong0)

lemma *get-maximum-level-skip-beginning*:
assumes *DH*: $\forall x \in \text{atms-of } D. x \notin \text{atm-of ` lits-of-l } c$
shows *get-maximum-level* $(c @ H) D = \text{get-maximum-level } H D$
proof –
have $(\text{get-level } (c @ H)) \text{ ` set-mset } D = (\text{get-level } H) \text{ ` set-mset } D$
apply (*rule image-cong*)
apply *simp*
using *DH* **unfolding** *atms-of-def* **by** *auto*
then show *?thesis* **using** *DH* **unfolding** *get-maximum-level-def* **by** *auto*
qed

lemma *get-maximum-level-D-single-propagated*:
get-maximum-level $[\text{Propagated } x21 \ x22] D = 0$
unfolding *get-maximum-level-def* **by** (*simp add: image-constant-conv*)

lemma *get-maximum-level-skip-un-decided-not-present*:
assumes
 $\forall L \in \#D. \text{atm-of } L \notin \text{atm-of ` lits-of-l } M$ **and**
 $\forall m \in \text{set } M. \neg \text{is-decided } m$
shows *get-maximum-level* $(M @ aa) D = \text{get-maximum-level } aa D$
using *assms* **unfolding** *get-maximum-level-def* **by** *simp*

lemma *get-maximum-level-union-mset*:
get-maximum-level $M (A \# \cup B) = \text{get-maximum-level } M (A + B)$
unfolding *get-maximum-level-def* **by** (*auto simp: image-Un*)

lemma *count-decided-rev*[simp]:
count-decided $(\text{rev } M) = \text{count-decided } M$

```

by (auto simp: rev-filter[symmetric])

lemma count-decided-ge-get-level[simp]:
  count-decided  $M \geq$  get-level  $M L$ 
by (induct  $M$  rule: ann-lit-list-induct) (auto simp add: le-max-iff-disj)

lemma count-decided-ge-get-maximum-level:
  count-decided  $M \geq$  get-maximum-level  $M D$ 
  using get-maximum-level-exists-lit-of-max-level unfolding Bex-def
  by (metis get-maximum-level-empty count-decided-ge-get-level le0)

fun get-all-mark-of-propagated where
  get-all-mark-of-propagated [] = [] |
  get-all-mark-of-propagated (Decided - #  $L$ ) = 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: ann-lit-list-induct) auto

```

Properties about the levels

```

lemma atm-lit-of-set-lits-of-l:
  ( $\lambda l.$  atm-of (lit-of  $l$ )) ' set  $xs =$  atm-of ' lits-of- $l$   $xs$ 
  unfolding lits-of-def by auto

lemma le-count-decided-decomp:
  assumes no-dup  $M$ 
  shows  $i < \text{count-decided } M \longleftrightarrow (\exists c K c'. M = c @ \text{Decided } K \# c' \wedge \text{get-level } M K = \text{Suc } i)$ 
  (is  $?A \longleftrightarrow ?B$ )
proof
  assume ? $B$ 
  then obtain  $c K c'$  where
     $M = c @ \text{Decided } K \# c'$  and  $\text{get-level } M K = \text{Suc } i$ 
  by blast
  then show ? $A$  using count-decided-ge-get-level[of  $K M$ ] by auto
next
  assume ? $A$ 
  then show ? $B$ 
  using  $\langle \text{no-dup } M \rangle$ 
  proof (induction  $M$  rule: ann-lit-list-induct)
    case Nil
    then show ?case by simp
  next
    case (Decided  $L M$ ) note  $IH = \text{this}(1)$  and  $i = \text{this}(2)$  and  $n-d = \text{this}(3)$ 
    then have  $n-d-M$ : no-dup  $M$  by simp
    show ?case
    proof (cases  $i < \text{count-decided } M$ )
      case True
      then obtain  $c K c'$  where
         $M: M = c @ \text{Decided } K \# c'$  and  $\text{lev-}K$ :  $\text{get-level } M K = \text{Suc } i$ 
      using  $IH$   $n-d-M$  by blast
      show ?thesis
      apply (rule exI[of - Decided  $L \# c$ ])
      apply (rule exI[of -  $K$ ])
      apply (rule exI[of -  $c'$ ])

```

```

    using lev-K n-d unfolding M by auto
next
  case False
  show ?thesis
    apply (rule exI[of - []])
    apply (rule exI[of - L])
    apply (rule exI[of - M])
    using False i by auto
  qed
next
  case (Propagated L mark' M) note i = this(2) and n-d = this(3) and IH = this(1)
  then obtain c K c' where
    M: M = c @ Decided K # c' and lev-K: get-level M K = Suc i
    by auto
  show ?case
    apply (rule exI[of - Propagated L mark' # c])
    apply (rule exI[of - K])
    apply (rule exI[of - c])
    using lev-K n-d unfolding M by (auto simp: atm-lit-of-set-lits-of-l)
  qed
qed

end
theory CDCL-W
imports List-More CDCL-W-Level Wellfounded-More Partial-Annotated-Clausal-Logic

begin

```


Chapter 6

Weidenbach's CDCL

The organisation of the development is the following:

- `CDCL_W.thy` contains the specification of the rules: the rules and the strategy are defined, and we prove the correctness of CDCL.
- `CDCL_W_Termination.thy` contains the proof of termination.
- `CDCL_W_Merge.thy` contains a variant of the calculus: some rules of the raw calculus are always applied together (like the rules analysing the conflict and then backtracking). We define an equivalent version of the calculus where these rules are applied together. This is useful for implementations.
- `CDCL_WNOT.thy` proves the inclusion of Weidenbach's version of CDCL in NOT's version. We use here the version defined in `CDCL_W_Merge.thy`. We need this, because NOT's backjump corresponds to multiple applications of three rules in Weidenbach's calculus. We show also the termination of the calculus without strategy.

We have some variants build on the top of Weidenbach's CDCL calculus:

- `CDCL_W_Incremental.thy` adds incrementality on the top of `CDCL_W.thy`. The way we are doing it is not compatible with `CDCL_W_Merge.thy`, because we add conflicts and the `CDCL_W_Merge.thy` cannot analyse conflicts added externally, because the conflict and analyse are merged.
- `CDCL_W_Restart.thy` adds restart. It is built on the top of `CDCL_W_Merge.thy`.

6.1 Weidenbach's CDCL with Multisets

`declare upt.simps(\mathbb{Z})[simp del]`

6.1.1 The State

We will abstract the representation of clause and clauses via two locales. We here use multisets, contrary to `CDCL_W_Abstract_State.thy` where we assume only the existence of a conversion to the state.

`locale stateW-ops =`

fixes

trail :: 'st \Rightarrow ('v, 'v clause) ann-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, 'v clause) ann-lit \Rightarrow 'st \Rightarrow 'st **and**
tl-trail :: 'st \Rightarrow 'st **and**
add-learned-cls :: 'v clause \Rightarrow 'st \Rightarrow 'st **and**
remove-cls :: 'v clause \Rightarrow 'st \Rightarrow 'st **and**
update-backtrack-lvl :: nat \Rightarrow 'st \Rightarrow 'st **and**
update-conflicting :: 'v clause option \Rightarrow 'st \Rightarrow 'st **and**

init-state :: 'v clauses \Rightarrow 'st

begin

abbreviation *hd-trail* :: 'st \Rightarrow ('v, 'v clause) ann-lit **where**
hd-trail *S* \equiv *hd* (*trail* *S*)

definition *clauses* :: 'st \Rightarrow 'v clauses **where**
clauses *S* = *init-clss* *S* + *learned-clss* *S*

abbreviation *resolve-cls* **where**

resolve-cls *L* *D'* *E* \equiv *remove1-mset* ($-L$) *D'* $\# \cup$ *remove1-mset* *L* *E*

abbreviation *state* :: 'st \Rightarrow ('v, 'v clause) ann-lits \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*)
end

We are using an abstract state to abstract away the detail of the implementation: we do not need to know how the clauses are represented internally, we just need to know that they can be converted to multisets.

Weidenbach state is a five-tuple composed of:

1. the trail is a list of decided literals;
2. the initial set of clauses (that is not changed during the whole calculus);
3. the learned clauses (clauses can be added or remove);
4. the maximum level of the trail;
5. the conflicting clause (if any has been found so far).

There are two different clause representation: one for the conflicting clause ('v *Partial-Clausal-Logic.clause*, standing for conflicting clause) and one for the initial and learned clauses ('v *Partial-Clausal-Logic.clause*, standing for clause). The representation of the clauses annotating literals in the trail is slightly different: being able to convert it to 'v *Partial-Clausal-Logic.clause* is enough (needed for function *hd-trail* below).

There are several axioms to state the independance of the different fields of the state: for example, adding a clause to the learned clauses does not change the trail.

locale *state_W* =

stateW-ops

— functions about the state:

— getter:

trail init-clss learned-clss backtrack-lvl conflicting

— setter:

*cons-trail tl-trail add-learned-clss remove-clss update-backtrack-lvl
update-conflicting*

— Some specific states:

init-state

for

trail :: 'st \Rightarrow ('v, 'v clause) ann-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, 'v clause) ann-lit \Rightarrow 'st \Rightarrow 'st **and**

tl-trail :: '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 +

assumes

cons-trail:

$\bigwedge S'. \text{state } st = (M, S') \implies$
state (cons-trail L st) = (L # M, S') **and**

tl-trail:

$\bigwedge S'. \text{state } st = (M, S') \implies \text{state } (tl\text{-trail } st) = (tl\ M, S') \text{ **and**}$

remove-clss:

$\bigwedge S'. \text{state } st = (M, N, U, S') \implies$
state (remove-clss C st) =
(M, removeAll-mset C N, removeAll-mset C U, S') **and**

add-learned-clss:

$\bigwedge S'. \text{state } st = (M, N, U, S') \implies$
state (add-learned-clss C st) = (M, N, {#C#} + U, S') **and**

update-backtrack-lvl:

$\bigwedge S'. \text{state } st = (M, N, U, k, S') \implies$
state (update-backtrack-lvl k' st) = (M, N, U, k', S') **and**

update-conflicting:

state st = (M, N, U, k, D) \implies
state (update-conflicting E st) = (M, N, U, k, E) **and**

init-state:

state (init-state N) = ([], N, {#}, 0, None)

begin

lemma

trail-cons-trail[simp]:

$trail (cons-trail L st) = L \# trail st$ **and**
 $trail-tl-trail[simp]: trail (tl-trail st) = tl (trail st)$ **and**
 $trail-add-learned-cls[simp]:$
 $trail (add-learned-cls C st) = trail st$ **and**
 $trail-remove-cls[simp]:$
 $trail (remove-cls C st) = trail st$ **and**
 $trail-update-backtrack-lvl[simp]: trail (update-backtrack-lvl k st) = trail st$ **and**
 $trail-update-conflicting[simp]: trail (update-conflicting E st) = trail st$ **and**

$init-clss-cons-trail[simp]:$
 $init-clss (cons-trail M st) = init-clss st$
and
 $init-clss-tl-trail[simp]:$
 $init-clss (tl-trail st) = init-clss st$ **and**
 $init-clss-add-learned-cls[simp]:$
 $init-clss (add-learned-cls C st) = init-clss st$ **and**
 $init-clss-remove-cls[simp]:$
 $init-clss (remove-cls C st) = removeAll-mset C (init-clss st)$ **and**
 $init-clss-update-backtrack-lvl[simp]:$
 $init-clss (update-backtrack-lvl k st) = init-clss st$ **and**
 $init-clss-update-conflicting[simp]:$
 $init-clss (update-conflicting E st) = init-clss st$ **and**

$learned-clss-cons-trail[simp]:$
 $learned-clss (cons-trail M st) = learned-clss st$ **and**
 $learned-clss-tl-trail[simp]:$
 $learned-clss (tl-trail st) = learned-clss st$ **and**
 $learned-clss-add-learned-cls[simp]:$
 $learned-clss (add-learned-cls C st) = \{\#C\# \} + learned-clss st$ **and**
 $learned-clss-remove-cls[simp]:$
 $learned-clss (remove-cls C st) = removeAll-mset C (learned-clss st)$ **and**
 $learned-clss-update-backtrack-lvl[simp]:$
 $learned-clss (update-backtrack-lvl k st) = learned-clss st$ **and**
 $learned-clss-update-conflicting[simp]:$
 $learned-clss (update-conflicting E st) = learned-clss st$ **and**

$backtrack-lvl-cons-trail[simp]:$
 $backtrack-lvl (cons-trail M st) = backtrack-lvl st$ **and**
 $backtrack-lvl-tl-trail[simp]:$
 $backtrack-lvl (tl-trail st) = backtrack-lvl st$ **and**
 $backtrack-lvl-add-learned-cls[simp]:$
 $backtrack-lvl (add-learned-cls C st) = backtrack-lvl st$ **and**
 $backtrack-lvl-remove-cls[simp]:$
 $backtrack-lvl (remove-cls C st) = backtrack-lvl st$ **and**
 $backtrack-lvl-update-backtrack-lvl[simp]:$
 $backtrack-lvl (update-backtrack-lvl k st) = k$ **and**
 $backtrack-lvl-update-conflicting[simp]:$
 $backtrack-lvl (update-conflicting E st) = backtrack-lvl st$ **and**

$conflicting-cons-trail[simp]:$
 $conflicting (cons-trail M st) = conflicting st$ **and**
 $conflicting-tl-trail[simp]:$
 $conflicting (tl-trail st) = conflicting st$ **and**
 $conflicting-add-learned-cls[simp]:$
 $conflicting (add-learned-cls C st) = conflicting st$
and

conflicting-remove-cls[simp]:
conflicting (*remove-cls* *C* *st*) = *conflicting* *st* **and**
conflicting-update-backtrack-lvl[simp]:
conflicting (*update-backtrack-lvl* *k* *st*) = *conflicting* *st* **and**
conflicting-update-conflicting[simp]:
conflicting (*update-conflicting* *E* *st*) = *E* **and**

init-state-trail[simp]: *trail* (*init-state* *N*) = [] **and**
init-state-clss[simp]: *init-clss* (*init-state* *N*) = *N* **and**
init-state-learned-clss[simp]: *learned-clss* (*init-state* *N*) = {#}
init-state-backtrack-lvl[simp]: *backtrack-lvl* (*init-state* *N*) = 0 **and**
init-state-conflicting[simp]: *conflicting* (*init-state* *N*) = None

using *cons-trail*[of *st*] *tl-trail*[of *st*] *add-learned-cls*[of *st* - - - *C*]
update-backtrack-lvl[of *st* - - - - *k*] *update-conflicting*[of *st* - - - - *E*]
remove-cls[of *st* - - - - *C*]
init-state[of *N*]
by (*cases* *state* *st*; *auto* *simp*;) +

lemma

shows

clauses-cons-trail[simp]:
clauses (*cons-trail* *M* *S*) = *clauses* *S* **and**

clss-tl-trail[simp]: *clauses* (*tl-trail* *S*) = *clauses* *S* **and**
clauses-add-learned-cls-unfolded:
clauses (*add-learned-cls* *U* *S*) = {#*U*#} + *learned-clss* *S* + *init-clss* *S*
and
clauses-update-backtrack-lvl[simp]: *clauses* (*update-backtrack-lvl* *k* *S*) = *clauses* *S* **and**
clauses-update-conflicting[simp]: *clauses* (*update-conflicting* *D* *S*) = *clauses* *S* **and**
clauses-remove-cls[simp]:
clauses (*remove-cls* *C* *S*) = *removeAll-mset* *C* (*clauses* *S*) **and**
clauses-add-learned-cls[simp]:
clauses (*add-learned-cls* *C* *S*) = {#*C*#} + *clauses* *S* **and**
clauses-init-state[simp]: *clauses* (*init-state* *N*) = *N*
by (*auto* *simp*; *ac-simps* *replicate-mset-plus* *clauses-def* *intro*; *multiset-eqI*)

abbreviation *incr-lvl* :: '*st* ⇒ '*st* **where**

incr-lvl *S* ≡ *update-backtrack-lvl* (*backtrack-lvl* *S* + 1) *S*

definition *state-eq* :: '*st* ⇒ '*st* ⇒ *bool* (*infix* ~ 50) **where**

S ~ *T* ⟷ *state* *S* = *state* *T*

lemma *state-eq-ref*[*simp*, *intro*]:

S ~ *S*

unfolding *state-eq-def* **by** *auto*

lemma *state-eq-sym*:

S ~ *T* ⟷ *T* ~ *S*

unfolding *state-eq-def* **by** *auto*

lemma *state-eq-trans*:

S ~ *T* ⟹ *T* ~ *U* ⟹ *S* ~ *U*

unfolding *state-eq-def* **by** *auto*

lemma

shows

state-eq-trail: $S \sim T \implies \text{trail } S = \text{trail } T$ **and**
state-eq-init-clss: $S \sim T \implies \text{init-clss } S = \text{init-clss } T$ **and**
state-eq-learned-clss: $S \sim T \implies \text{learned-clss } S = \text{learned-clss } T$ **and**
state-eq-backtrack-lvl: $S \sim T \implies \text{backtrack-lvl } S = \text{backtrack-lvl } T$ **and**
state-eq-conflicting: $S \sim T \implies \text{conflicting } S = \text{conflicting } T$ **and**
state-eq-clauses: $S \sim T \implies \text{clauses } S = \text{clauses } T$ **and**
state-eq-undefined-lit: $S \sim T \implies \text{undefined-lit } (\text{trail } S) L = \text{undefined-lit } (\text{trail } T) L$
unfolding *state-eq-def* *clauses-def* **by** *auto*

lemma *state-eq-conflicting-None*:

$S \sim T \implies \text{conflicting } T = \text{None} \implies \text{conflicting } S = \text{None}$
unfolding *state-eq-def* *clauses-def* **by** *auto*

We combine all simplification rules about $op \sim$ in a single list of theorems. While they are handy as simplification rule as long as we are working on the state, they also cause a *huge* slow-down in all other cases.

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*
state-eq-conflicting-None

function *reduce-trail-to* :: 'a list \Rightarrow 'st \Rightarrow 'st **where**

reduce-trail-to *F* *S* =
 (if *length* (*trail* *S*) = *length* *F* \vee *trail* *S* = [] then *S* else *reduce-trail-to* *F* (*tl-trail* *S*))
by *fast+*

termination

by (*relation measure* ($\lambda(-, S). \text{length } (\text{trail } S)$)) *simp-all*

declare *reduce-trail-to.simps*[*simp del*]

lemma

shows

reduce-trail-to-Nil[*simp*]: $\text{trail } S = [] \implies \text{reduce-trail-to } F S = S$ **and**
reduce-trail-to-eq-length[*simp*]: $\text{length } (\text{trail } S) = \text{length } F \implies \text{reduce-trail-to } F S = S$
by (*auto simp: reduce-trail-to.simps*)

lemma *reduce-trail-to-length-ne*:

$\text{length } (\text{trail } S) \neq \text{length } F \implies \text{trail } S \neq [] \implies$
 $\text{reduce-trail-to } F S = \text{reduce-trail-to } F (\text{tl-trail } S)$
by (*auto simp: reduce-trail-to.simps*)

lemma *trail-reduce-trail-to-length-le*:

assumes $\text{length } F > \text{length } (\text{trail } S)$
shows $\text{trail } (\text{reduce-trail-to } F S) = []$
using *assms* **apply** (*induction* *F S* *rule: reduce-trail-to.induct*)
by (*metis* (*no-types*, *hide-lams*) *length-tl* *less-imp-diff-less* *less-irrefl* *trail-tl-trail*
reduce-trail-to.simps)

lemma *trail-reduce-trail-to-Nil*[*simp*]:

$\text{trail } (\text{reduce-trail-to } [] S) = []$
apply (*induction* $[[::('v, 'v \text{ clause}) \text{ ann-lits } S \text{ rule: } \text{reduce-trail-to.induct})]$)
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 *clauses* (*reduce-trail-to* ([::'a list] (*tl-trail Sa*))) = *clauses* (*tl-trail Sa*)
 \vee *trail Sa* = []
by *fastforce*
then show *clauses* (*reduce-trail-to* ([::'a list] *Sa*)) = *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 *trail S = F' @ F*
shows *trail* (*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]*:
clauses (*reduce-trail-to F S*) = *clauses S*
apply (*induction F S rule: reduce-trail-to.induct*)
by (*metis clss-tl-trail reduce-trail-to.simps*)

lemma *conflicting-update-trail[simp]*:
conflicting (*reduce-trail-to F S*) = *conflicting S*
apply (*induction F S rule: reduce-trail-to.induct*)
by (*metis conflicting-tl-trail reduce-trail-to.simps*)

lemma *backtrack-lvl-update-trail[simp]*:
backtrack-lvl (*reduce-trail-to F S*) = *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-trail[simp]*:
init-clss (*reduce-trail-to F S*) = *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-trail[simp]*:
learned-clss (*reduce-trail-to F S*) = *learned-clss S*
apply (*induction F S rule: reduce-trail-to.induct*)
by (*metis learned-clss-tl-trail reduce-trail-to.simps*)

lemma *conflicting-reduce-trail-to[simp]*:
conflicting (*reduce-trail-to F S*) = *None* \longleftrightarrow *conflicting S = None*
apply (*induction F S rule: reduce-trail-to.induct*)
by (*metis conflicting-update-trail map-option-is-None*)

lemma *trail-eq-reduce-trail-to-eq*:
trail S = trail T \implies *trail* (*reduce-trail-to F S*) = *trail* (*reduce-trail-to F T*)
apply (*induction F S arbitrary: T rule: reduce-trail-to.induct*)
by (*metis trail-tl-trail reduce-trail-to.simps*)

lemma *reduce-trail-to-state-eq_{NOT}-compatible*:
assumes *ST: S ~ T*
shows *reduce-trail-to F S ~ reduce-trail-to F T*
proof –
have *trail* (*reduce-trail-to F S*) = *trail* (*reduce-trail-to F T*)
using *trail-eq-reduce-trail-to-eq[of S T F] ST* **by** *auto*

then show *?thesis* **using** *ST* **by** (*auto simp del: state-simp simp: state-eq-def*)
qed

lemma *reduce-trail-to-trail-tl-trail-decomp*[*simp*]:
 $trail\ S = F' @ Decided\ K \# F \implies (trail\ (reduce-trail-to\ F\ S)) = F$
apply (*rule reduce-trail-to-skip-beginning*[*of - F' @ Decided K # []*])
by (*cases F'*) (*auto simp add:tl-append reduce-trail-to-skip-beginning*)

lemma *reduce-trail-to-add-learned-cls*[*simp*]:
 $trail\ (reduce-trail-to\ F\ (add-learned-cls\ C\ S)) = trail\ (reduce-trail-to\ F\ S)$
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*]:
 $trail\ (reduce-trail-to\ F\ (update-backtrack-lvl\ k\ S)) = trail\ (reduce-trail-to\ F\ S)$
by (*rule trail-eq-reduce-trail-to-eq*) *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 rule: reduce-trail-to.induct*)
by (*simp add: reduce-trail-to.simps*)

lemma *trail-reduce-trail-to-drop*:
 $trail\ (reduce-trail-to\ F\ S) =$
 $(if\ length\ (trail\ S) \geq length\ F$
 $\ then\ drop\ (length\ (trail\ S) - length\ F)\ (trail\ S)$
 $\ else\ [])$
apply (*induction F S rule: reduce-trail-to.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 (*metis diff-is-0-eq drop-Cons' length-Cons nat-le-linear nat-less-le*
 $reduce-trail-to-eq-length\ trail-reduce-trail-to-length-le$)
apply (*subgoal-tac Suc (length list) - length F = Suc (length list - length F)*)
by (*auto simp add: reduce-trail-to-length-ne*)

lemma *in-get-all-ann-decomposition-trail-update-trail*[*simp*]:
assumes *H*: $(L \# M1, M2) \in set\ (get-all-ann-decomposition\ (trail\ S))$
shows $trail\ (reduce-trail-to\ M1\ S) = M1$
proof –
obtain *K* **where**
 $L: L = Decided\ K$
using *H* **by** (*cases L*) (*auto dest!: in-get-all-ann-decomposition-decided-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*])
 $(auto\ simp: tr-S\ L)$

qed

lemma *conflicting-cons-trail-conflicting*[simp]:
assumes *undefined-lit* (*trail* *S*) (*lit-of* *L*)
shows
 $\text{conflicting } (\text{cons-trail } L \ S) = \text{None} \longleftrightarrow \text{conflicting } S = \text{None}$
using *assms* *conflicting-cons-trail*[of *L* *S*] *map-option-is-None* **by** *fastforce*+

lemma *conflicting-add-learned-cls-conflicting*[simp]:
 $\text{conflicting } (\text{add-learned-cls } C \ S) = \text{None} \longleftrightarrow \text{conflicting } S = \text{None}$
by *fastforce*+

lemma *conflicting-update-backtrack-lvl*[simp]:
 $\text{conflicting } (\text{update-backtrack-lvl } k \ S) = \text{None} \longleftrightarrow \text{conflicting } S = \text{None}$
using *map-option-is-None* *conflicting-update-backtrack-lvl*[of *k* *S*] **by** *fastforce*+

end — end of *state_W* locale

6.1.2 CDCL Rules

Because of the strategy we will later use, we distinguish propagate, conflict from the other rules

locale *conflict-driven-clause-learning_W* =
state_W
 — functions for the state:
 — access functions:
trail *init-clss* *learned-clss* *backtrack-lvl* *conflicting*
 — changing state:
cons-trail *tl-trail* *add-learned-cls* *remove-cls* *update-backtrack-lvl*
update-conflicting
 — get state:
init-state
for
trail :: '*st* ⇒ ('*v*, '*v* clause) ann-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*, '*v* clause) ann-lit ⇒ '*st* ⇒ '*st* **and**
tl-trail :: '*st* ⇒ '*st* **and**
add-learned-cls :: '*v* clause ⇒ '*st* ⇒ '*st* **and**
remove-cls :: '*v* clause ⇒ '*st* ⇒ '*st* **and**
update-backtrack-lvl :: nat ⇒ '*st* ⇒ '*st* **and**
update-conflicting :: '*v* clause option ⇒ '*st* ⇒ '*st* **and**

init-state :: '*v* clauses ⇒ '*st*
begin

inductive *propagate* :: '*st* ⇒ '*st* ⇒ bool **for** *S* :: '*st* **where**
propagate-rule: *conflicting* *S* = None ⇒
 $E \in \# \text{ clauses } S \Rightarrow$
 $L \in \# E \Rightarrow$
 $\text{trail } S \models_{as} CNot (E - \{\#L\}) \Rightarrow$
 $\text{undefined-lit } (\text{trail } S) \ L \Rightarrow$

$T \sim \text{cons-trail } (\text{Propagated } L \ E) \ S \implies$
 $\text{propagate } S \ T$

inductive-cases propagateE : $\text{propagate } S \ T$

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

$\text{conflicting } S = \text{None} \implies$
 $D \in \# \text{ clauses } S \implies$
 $\text{trail } S \models_{\text{as}} \text{CNot } D \implies$
 $T \sim \text{update-conflicting } (\text{Some } D) \ S \implies$
 $\text{conflict } S \ T$

inductive-cases conflictE : $\text{conflict } S \ T$

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

$\text{conflicting } S = \text{Some } D \implies$
 $L \in \# D \implies$
 $(\text{Decided } K \ \# \ M1, \ M2) \in \text{set } (\text{get-all-ann-decomposition } (\text{trail } S)) \implies$
 $\text{get-level } (\text{trail } S) \ L = \text{backtrack-lvl } S \implies$
 $\text{get-level } (\text{trail } S) \ L = \text{get-maximum-level } (\text{trail } S) \ D \implies$
 $\text{get-maximum-level } (\text{trail } S) \ (D - \{\#L\# \}) \equiv i \implies$
 $\text{get-level } (\text{trail } S) \ K = i + 1 \implies$
 $T \sim \text{cons-trail } (\text{Propagated } L \ D)$
 $\quad (\text{reduce-trail-to } M1$
 $\quad \quad (\text{add-learned-cls } D$
 $\quad \quad \quad (\text{update-backtrack-lvl } i$
 $\quad \quad \quad \quad (\text{update-conflicting } \text{None } S)))) \implies$
 $\text{backtrack } S \ T$

inductive-cases backtrackE : $\text{backtrack } S \ T$

thm backtrackE

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

$\text{conflicting } S = \text{None} \implies$
 $\text{undefined-lit } (\text{trail } S) \ L \implies$
 $\text{atm-of } L \in \text{atms-of-mm } (\text{init-clss } S) \implies$
 $T \sim \text{cons-trail } (\text{Decided } L) \ (\text{incr-lvl } S) \implies$
 $\text{decide } S \ T$

inductive-cases decideE : $\text{decide } S \ T$

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

$\text{trail } S = \text{Propagated } L \ C' \ \# \ M \implies$
 $\text{conflicting } S = \text{Some } E \implies$
 $-L \notin \# E \implies$
 $E \neq \{\#\} \implies$
 $T \sim \text{tl-trail } S \implies$
 $\text{skip } S \ T$

inductive-cases skipE : $\text{skip } S \ T$

$\text{get-maximum-level } (\text{Propagated } L \ (C + \{\#L\# \}) \ \# \ M) \ D = k \vee k = 0$ (that was in a previous

version of the book) is equivalent to *get-maximum-level* (*Propagated* $L (C + \{\#L\# \}) \# M$) $D = k$, when the structural invariants holds.

inductive *resolve* :: 'st \Rightarrow 'st \Rightarrow bool **for** $S ::$ 'st **where**

resolve-rule: $\text{trail } S \neq [] \implies$

$\text{hd-trail } S = \text{Propagated } L \ E \implies$

$L \in \# \ E \implies$

$\text{conflicting } S = \text{Some } D' \implies$

$-L \in \# \ D' \implies$

$\text{get-maximum-level } (\text{trail } S) ((\text{remove1-mset } (-L) \ D')) = \text{backtrack-lvl } S \implies$

$T \sim \text{update-conflicting } (\text{Some } (\text{resolve-cls } L \ D' \ E))$

$(\text{tl-trail } S) \implies$

resolve $S \ T$

inductive-cases *resolveE*: *resolve* $S \ T$

inductive *restart* :: 'st \Rightarrow 'st \Rightarrow bool **for** $S ::$ 'st **where**

restart: $\text{state } S = (M, N, U, k, \text{None}) \implies$

$\neg M \models_{\text{asm}} \text{clauses } S \implies$

$U' \subseteq \# \ U \implies$

$\text{state } T = ([], N, U', 0, \text{None}) \implies$

restart $S \ T$

inductive-cases *restartE*: *restart* $S \ T$

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:

$\text{conflicting } S = \text{None} \implies$

$C \in \# \ \text{learned-clss } S \implies$

$\neg(\text{trail } S) \models_{\text{asm}} \text{clauses } S \implies$

$C \notin \text{set } (\text{get-all-mark-of-propagated } (\text{trail } S)) \implies$

$C \notin \# \ \text{init-clss } S \implies$

$T \sim \text{remove-cls } C \ S \implies$

forget $S \ T$

inductive-cases *forgetE*: *forget* $S \ T$

inductive *cdcl_W-rf* :: 'st \Rightarrow 'st \Rightarrow bool **for** $S ::$ 'st **where**

restart: $\text{restart } S \ T \implies \text{cdcl}_W\text{-rf } S \ T \mid$

forget: $\text{forget } S \ T \implies \text{cdcl}_W\text{-rf } S \ T$

inductive *cdcl_W-bj* :: 'st \Rightarrow 'st \Rightarrow bool **where**

skip: $\text{skip } S \ S' \implies \text{cdcl}_W\text{-bj } S \ S' \mid$

resolve: $\text{resolve } S \ S' \implies \text{cdcl}_W\text{-bj } S \ S' \mid$

backtrack: $\text{backtrack } S \ S' \implies \text{cdcl}_W\text{-bj } S \ S'$

inductive-cases *cdcl_W-bjE*: *cdcl_W-bj* $S \ T$

inductive *cdcl_W-o* :: 'st \Rightarrow 'st \Rightarrow bool **for** $S ::$ 'st **where**

decide: $\text{decide } S \ S' \implies \text{cdcl}_W\text{-o } S \ S' \mid$

bj: $\text{cdcl}_W\text{-bj } S \ S' \implies \text{cdcl}_W\text{-o } S \ S'$

inductive *cdcl_W* :: 'st \Rightarrow 'st \Rightarrow bool **for** $S ::$ 'st **where**

propagate: $\text{propagate } S \ S' \implies \text{cdcl}_W \ S \ S' \mid$

conflict: $\text{conflict } S \ S' \implies \text{cdcl}_W \ S \ S' \mid$

other: $cdcl_W\text{-}o\ S\ S' \implies cdcl_W\ S\ S'$
rf: $cdcl_W\text{-}rf\ S\ S' \implies cdcl_W\ S\ S'$

lemma *rtrancplp-propagate-is-rtrancplp-cdcl_W*:
 $propagate^{**}\ S\ S' \implies cdcl_W^{**}\ S\ S'$
apply (*induction rule*: *rtrancplp-induct*)
apply *simp*
apply (*frule* *propagate*)
using *rtrancplp-trans*[*of cdcl_W*] **by** *blast*

lemma *cdcl_W-all-rules-induct*[*consumes 1, case-names propagate conflict forget restart decide skip resolve backtrack*]:

fixes *S* :: '*st*
assumes
 $cdcl_W: cdcl_W\ S\ S' \text{ and}$
 $propagate: \bigwedge T. propagate\ S\ T \implies P\ S\ T \text{ and}$
 $conflict: \bigwedge T. conflict\ S\ T \implies P\ S\ T \text{ and}$
 $forget: \bigwedge T. forget\ S\ T \implies P\ S\ T \text{ and}$
 $restart: \bigwedge T. restart\ S\ T \implies P\ S\ T \text{ and}$
 $decide: \bigwedge T. decide\ S\ T \implies P\ S\ T \text{ and}$
 $skip: \bigwedge T. skip\ S\ T \implies P\ S\ T \text{ and}$
 $resolve: \bigwedge T. resolve\ S\ T \implies P\ S\ T \text{ and}$
 $backtrack: \bigwedge T. backtrack\ S\ T \implies P\ S\ T$
shows $P\ S\ S'$
using *assms*(1)
proof (*induct S' rule: cdcl_W.induct*)
case (*propagate S'*) **note** *propagate = this*(1)
then show ?*case* **using** *assms*(2) **by** *auto*
next
case (*conflict S'*)
then show ?*case* **using** *assms*(3) **by** *auto*
next
case (*other S'*)
then show ?*case*
proof (*induct rule: cdcl_W-o.induct*)
case (*decide U*)
then show ?*case* **using** *assms*(6) **by** *auto*
next
case (*bj S'*)
then show ?*case* **using** *assms*(7–9) **by** (*induction rule: cdcl_W-bj.induct*) *auto*
qed
next
case (*rf S'*)
then show ?*case*
by (*induct rule: cdcl_W-rf.induct*) (*fast dest: forget restart*)
qed

lemma *cdcl_W-all-induct*[*consumes 1, case-names propagate conflict forget restart decide skip resolve backtrack*]:

fixes *S* :: '*st*
assumes
 $cdcl_W: cdcl_W\ S\ S' \text{ and}$
 $propagateH: \bigwedge C\ L\ T. conflicting\ S = None \implies$
 $C \in \# \text{ clauses } S \implies$
 $L \in \# C \implies$
 $trail\ S \models_{as} CNot\ (remove1\text{-}mset\ L\ C) \implies$

$undefined\text{-}lit\ (trail\ S)\ L \implies$
 $T \sim cons\text{-}trail\ (Propagated\ L\ C)\ S \implies$
 $P\ S\ T\ \mathbf{and}$
 $conflictH: \bigwedge D\ T. conflicting\ S = None \implies$
 $D \in \# clauses\ S \implies$
 $trail\ S \models_{as}\ CNot\ D \implies$
 $T \sim update\text{-}conflicting\ (Some\ D)\ S \implies$
 $P\ S\ T\ \mathbf{and}$
 $forgetH: \bigwedge C\ T. conflicting\ S = None \implies$
 $C \in \# learned\text{-}clss\ S \implies$
 $\neg(trail\ S) \models_{asm}\ clauses\ S \implies$
 $C \notin set\ (get\text{-}all\text{-}mark\text{-}of\text{-}propagated\ (trail\ S)) \implies$
 $C \notin \# init\text{-}clss\ S \implies$
 $T \sim remove\text{-}cls\ C\ S \implies$
 $P\ S\ T\ \mathbf{and}$
 $restartH: \bigwedge T\ U. \neg trail\ S \models_{asm}\ clauses\ S \implies$
 $conflicting\ S = None \implies$
 $state\ T = ([], init\text{-}clss\ S, U, 0, None) \implies$
 $U \subseteq \# learned\text{-}clss\ S \implies$
 $P\ S\ T\ \mathbf{and}$
 $decideH: \bigwedge L\ T. conflicting\ S = None \implies$
 $undefined\text{-}lit\ (trail\ S)\ L \implies$
 $atm\text{-}of\ L \in atms\text{-}of\text{-}mm\ (init\text{-}clss\ S) \implies$
 $T \sim cons\text{-}trail\ (Decided\ L)\ (incr\text{-}lvl\ S) \implies$
 $P\ S\ T\ \mathbf{and}$
 $skipH: \bigwedge L\ C'\ M\ E\ T.$
 $trail\ S = Propagated\ L\ C'\ \# M \implies$
 $conflicting\ S = Some\ E \implies$
 $-L \notin \# E \implies E \neq \{\#\} \implies$
 $T \sim tl\text{-}trail\ S \implies$
 $P\ S\ T\ \mathbf{and}$
 $resolveH: \bigwedge L\ E\ M\ D\ T.$
 $trail\ S = Propagated\ L\ E\ \# M \implies$
 $L \in \# E \implies$
 $hd\text{-}trail\ S = Propagated\ L\ E \implies$
 $conflicting\ S = Some\ D \implies$
 $-L \in \# D \implies$
 $get\text{-}maximum\text{-}level\ (trail\ S)\ ((remove1\text{-}mset\ (-L)\ D)) = backtrack\text{-}lvl\ S \implies$
 $T \sim update\text{-}conflicting$
 $(Some\ (resolve\text{-}cls\ L\ D\ E))\ (tl\text{-}trail\ S) \implies$
 $P\ S\ T\ \mathbf{and}$
 $backtrackH: \bigwedge L\ D\ K\ i\ M1\ M2\ T.$
 $conflicting\ S = Some\ D \implies$
 $L \in \# D \implies$
 $(Decided\ K\ \# M1, M2) \in set\ (get\text{-}all\text{-}ann\text{-}decomposition\ (trail\ S)) \implies$
 $get\text{-}level\ (trail\ S)\ L = backtrack\text{-}lvl\ S \implies$
 $get\text{-}level\ (trail\ S)\ L = get\text{-}maximum\text{-}level\ (trail\ S)\ D \implies$
 $get\text{-}maximum\text{-}level\ (trail\ S)\ (remove1\text{-}mset\ L\ D) \equiv i \implies$
 $get\text{-}level\ (trail\ S)\ K = i+1 \implies$
 $T \sim cons\text{-}trail\ (Propagated\ L\ D)$
 $(reduce\text{-}trail\text{-}to\ M1$
 $(add\text{-}learned\text{-}cls\ D$
 $(update\text{-}backtrack\text{-}lvl\ i$
 $(update\text{-}conflicting\ None\ S)))) \implies$
 $P\ S\ T$
 $\mathbf{shows}\ P\ S\ S'$

```

using cdclW
proof (induct S S' rule: cdclW-all-rules-induct)
  case (propagate S')
  then show ?case
    by (auto elim!: propagateE intro!: propagateH)
next
  case (conflict S')
  then show ?case
    by (auto elim!: conflictE intro!: conflictH)
next
  case (restart S')
  then show ?case
    by (auto elim!: restartE intro!: restartH)
next
  case (decide T)
  then show ?case
    by (auto elim!: decideE intro!: decideH)
next
  case (backtrack S')
  then show ?case by (auto elim!: backtrackE intro!: backtrackH
    simp del: state-simp simp add: state-eq-def)
next
  case (forget S')
  then show ?case by (auto elim!: forgetE intro!: forgetH)
next
  case (skip S')
  then show ?case by (auto elim!: skipE intro!: skipH)
next
  case (resolve S')
  then show ?case
    by (cases trail S) (auto elim!: resolveE intro!: resolveH)
qed

```

lemma *cdcl_W-o-induct*[consumes 1, case-names decide skip resolve backtrack]:
fixes $S :: 'st$
assumes $cdcl_W: cdcl_W\text{-}o\ S\ T$ **and**
 $decideH: \bigwedge L\ T. \text{conflicting}\ S = \text{None} \implies \text{undefined-lit}\ (\text{trail}\ S)\ L$
 $\implies \text{atm-of}\ L \in \text{atms-of-mm}\ (\text{init-clss}\ S)$
 $\implies T \sim \text{cons-trail}\ (\text{Decided}\ L)\ (\text{incr-lvl}\ S)$
 $\implies P\ S\ T$ **and**
 $skipH: \bigwedge L\ C'\ M\ E\ T.$
 $\text{trail}\ S = \text{Propagated}\ L\ C'\ \# \ M \implies$
 $\text{conflicting}\ S = \text{Some}\ E \implies$
 $-L \notin \# E \implies E \neq \{\#\} \implies$
 $T \sim \text{tl-trail}\ S \implies$
 $P\ S\ T$ **and**
 $resolveH: \bigwedge L\ E\ M\ D\ T.$
 $\text{trail}\ S = \text{Propagated}\ L\ E\ \# \ M \implies$
 $L \in \# E \implies$
 $\text{hd-trail}\ S = \text{Propagated}\ L\ E \implies$
 $\text{conflicting}\ S = \text{Some}\ D \implies$
 $-L \in \# D \implies$
 $\text{get-maximum-level}\ (\text{trail}\ S)\ ((\text{remove1-mset}\ (-L)\ D)) = \text{backtrack-lvl}\ S \implies$
 $T \sim \text{update-conflicting}$
 $(\text{Some}\ (\text{resolve-cl}\ L\ D\ E))\ (\text{tl-trail}\ S) \implies$
 $P\ S\ T$ **and**

```

backtrackH:  $\bigwedge L D K i M1 M2 T.$ 
  conflicting  $S = \text{Some } D \implies$ 
   $L \in \# D \implies$ 
   $(\text{Decided } K \# M1, M2) \in \text{set } (\text{get-all-ann-decomposition } (\text{trail } S)) \implies$ 
   $\text{get-level } (\text{trail } S) L = \text{backtrack-lvl } S \implies$ 
   $\text{get-level } (\text{trail } S) L = \text{get-maximum-level } (\text{trail } S) D \implies$ 
   $\text{get-maximum-level } (\text{trail } S) (\text{remove1-mset } L D) \equiv i \implies$ 
   $\text{get-level } (\text{trail } S) K = i + 1 \implies$ 
   $T \sim \text{cons-trail } (\text{Propagated } L D)$ 
     $(\text{reduce-trail-to } M1$ 
       $(\text{add-learned-cls } D$ 
         $(\text{update-backtrack-lvl } i$ 
           $(\text{update-conflicting } \text{None } S)))) \implies$ 
   $P S T$ 
shows  $P S T$ 
using  $\text{cdcl}_W$  apply (induct  $T$  rule:  $\text{cdcl}_W\text{-o.induct}$ )
  using  $\text{assms}(2)$  apply (auto elim:  $\text{decideE}$ )[1]
apply (elim  $\text{cdcl}_W\text{-bjE}$  skipE resolveE backtrackE)
  apply (frule skipH; simp)
  apply (cases trail  $S$ ; auto elim!: resolveE intro!: resolveH)
apply (frule backtrackH; simp)
done

thm  $\text{cdcl}_W\text{-o.induct}$ 
lemma  $\text{cdcl}_W\text{-o-all-rules-induct}$ [consumes 1, case-names decide backtrack skip resolve]:
  fixes  $S T :: 'st$ 
  assumes
     $\text{cdcl}_W\text{-o } S T$  and
     $\bigwedge T. \text{decide } S T \implies P S T$  and
     $\bigwedge T. \text{backtrack } S T \implies P S T$  and
     $\bigwedge T. \text{skip } S T \implies P S T$  and
     $\bigwedge T. \text{resolve } S T \implies P S T$ 
  shows  $P S T$ 
  using  $\text{assms}$  by (induct  $T$  rule:  $\text{cdcl}_W\text{-o.induct}$ ) (auto simp:  $\text{cdcl}_W\text{-bj.simps}$ )

lemma  $\text{cdcl}_W\text{-o-rule-cases}$ [consumes 1, case-names decide backtrack skip resolve]:
  fixes  $S T :: 'st$ 
  assumes
     $\text{cdcl}_W\text{-o } S T$  and
     $\text{decide } S T \implies P$  and
     $\text{backtrack } S T \implies P$  and
     $\text{skip } S T \implies P$  and
     $\text{resolve } S T \implies P$ 
  shows  $P$ 
  using  $\text{assms}$  by (auto simp:  $\text{cdcl}_W\text{-o.simps}$   $\text{cdcl}_W\text{-bj.simps}$ )

```

6.1.3 Structural Invariants

Properties of the trail

We here establish that:

- the consistency of the trail;
- the fact that there is no duplicate in the trail.

lemma *backtrack-lit-skipped*:

assumes

L: *get-level* (*trail S*) *L* = *backtrack-lvl S* **and**

M1: (*Decided K* # *M1*, *M2*) ∈ *set* (*get-all-ann-decomposition* (*trail S*)) **and**

no-dup: *no-dup* (*trail S*) **and**

bt-l: *backtrack-lvl S* = *length* (*filter is-decided* (*trail S*)) **and**

lev-K: *get-level* (*trail S*) *K* = *i* + 1

shows *atm-of L* ∉ *atm-of* ‘*lits-of-l M1*

proof (*rule ccontr*)

let ?*M* = *trail S*

assume *L-in-M1*: ¬*atm-of L* ∉ *atm-of* ‘*lits-of-l M1*

obtain *c* **where**

Mc: *trail S* = *c* @ *M2* @ *Decided K* # *M1*

using *M1* **by** *blast*

have *atm-of L* ∉ *atm-of* ‘*lits-of-l c* **and** *atm-of L* ∉ *atm-of* ‘*lits-of-l M2* **and**

atm-of L ≠ *atm-of K* **and** *Kc*: *atm-of K* ∉ *atm-of* ‘*lits-of-l c* **and**

KM2: *atm-of K* ∉ *atm-of* ‘*lits-of-l M2*

using *L-in-M1 no-dup unfolding Mc lits-of-def* **by** *force+*

then have *g-M-eq-g-M1*: *get-level* ?*M L* = *get-level M1 L*

using *L-in-M1 unfolding Mc* **by** *auto*

then have *get-level M1 L* < *Suc i*

using *count-decided-ge-get-level[of L M1] KM2 lev-K Kc unfolding Mc*

by (*auto simp del: count-decided-ge-get-level*)

moreover have *Suc i* ≤ *backtrack-lvl S* **using** *bt-l KM2 lev-K Kc unfolding Mc* **by** (*simp add: Mc*)

ultimately show *False* **using** *L g-M-eq-g-M1* **by** *auto*

qed

lemma *cdcl_W-distinctinv-1*:

assumes

cdcl_W S S' **and**

no-dup (*trail S*) **and**

bt-lev: *backtrack-lvl S* = *count-decided* (*trail S*)

shows *no-dup* (*trail S'*)

using *assms*

proof (*induct rule: cdcl_W-all-induct*)

case (*backtrack L D K i M1 M2 T*) **note** *decomp* = *this(3)* **and** *L* = *this(4)* **and** *lev-K* = *this(7)*

and

T = *this(8)* **and** *n-d* = *this(9)*

obtain *c* **where** *Mc*: *trail S* = *c* @ *M2* @ *Decided K* # *M1*

using *decomp* **by** *auto*

have *no-dup* (*M2* @ *Decided K* # *M1*)

using *Mc n-d* **by** *fastforce*

moreover have *atm-of L* ∉ *atm-of* ‘*lits-of-l M1*

using *backtrack-lit-skipped[of L S K M1 M2 i] L decomp lev-K n-d bt-lev* **by** *fast*

moreover then have *undefined-lit M1 L*

by (*simp add: defined-lit-map lits-of-def image-image*)

ultimately show ?*case* **using** *decomp T n-d* **by** (*simp add: lits-of-def image-image*)

qed (*auto simp: defined-lit-map*)

Item 1 page 81 of Weidenbach’s book

lemma *cdcl_W-consistent-inv-2*:

assumes

cdcl_W S S' **and**

no-dup (*trail S*) **and**

backtrack-lvl S = *count-decided* (*trail S*)

shows *consistent-interp* (*lits-of-l* (*trail S'*))

using *cdcl_W-distinctinv-1* [*OF assms*] *distinct-consistent-interp* **by** *fast*

lemma *cdcl_W-o-bt*:

assumes

cdcl_W-o S S' **and**

backtrack-lvl S = count-decided (trail S) **and**

n-d[simp]: no-dup (trail S)

shows *backtrack-lvl S' = count-decided (trail S')*

using *assms*

proof (*induct rule: cdcl_W-o-induct*)

case (*backtrack L D K i M1 M2 T*) **note** *decomp = this(3)* **and** *levK = this(7)* **and** *T = this(8)*

and

level = this(9)

have [*simp*]: *trail (reduce-trail-to M1 S) = M1*

using *decomp* **by** *auto*

obtain *c* **where** *M: trail S = c @ M2 @ Decided K # M1* **using** *decomp* **by** *auto*

moreover **have** *atm-of L ∉ atm-of ' lits-of-l M1*

using *backtrack-lit-skipped[of L S K M1 M2 i]* *backtrack(4,8,9) levK decomp*

by (*fastforce simp add: lits-of-def*)

moreover **then have** *undefined-lit M1 L*

by (*simp add: defined-lit-map lits-of-def image-image*)

moreover

have *atm-of K ∉ atm-of ' lits-of-l M1* **and** *atm-of K ∉ atm-of ' lits-of-l c*

and *atm-of K ∉ atm-of ' lits-of-l M2*

using *T n-d levK unfolding M* **by** (*auto simp: lits-of-def*)

ultimately show *?case*

using *T levK unfolding M* **by** (*auto dest!: append-cons-eq-upt-length*)

qed *auto*

lemma *cdcl_W-rf-bt*:

assumes

cdcl_W-rf S S' **and**

backtrack-lvl S = count-decided (trail S)

shows *backtrack-lvl S' = count-decided (trail S')*

using *assms* **by** (*induct rule: cdcl_W-rf.induct*) (*auto elim: restartE forgetE*)

Item 7 page 81 of Weidenbach's book

lemma *cdcl_W-bt*:

assumes

cdcl_W S S' **and**

backtrack-lvl S = count-decided (trail S) **and**

no-dup (trail S)

shows *backtrack-lvl S' = count-decided (trail S')*

using *assms* **by** (*induct rule: cdcl_W.induct*) (*auto simp: cdcl_W-o-bt cdcl_W-rf-bt*

elim: conflictE propagateE)

We write $1 + \text{count-decided}(\text{trail } S)$ instead of *backtrack-lvl S* to avoid non termination of rewriting.

definition *cdcl_W-M-level-inv* :: *'st* \Rightarrow *bool* **where**

cdcl_W-M-level-inv S \longleftrightarrow

consistent-interp (lits-of-l (trail S))

\wedge *no-dup (trail S)*

\wedge *backtrack-lvl S = count-decided (trail S)*

lemma *cdcl_W-M-level-inv-decomp*:

```

assumes cdclW-M-level-inv S
shows
  consistent-interp (lits-of-l (trail S)) and
  no-dup (trail S)
using assms unfolding cdclW-M-level-inv-def by fastforce+
```

lemma *cdcl_W-consistent-inv*:

```

fixes S S' :: 'st
assumes
  cdclW S S' and
  cdclW-M-level-inv S
shows cdclW-M-level-inv S'
using assms cdclW-consistent-inv-2 cdclW-distinctinv-1 cdclW-bt
unfolding cdclW-M-level-inv-def by meson+
```

lemma *rtrancpl-cdcl_W-consistent-inv*:

```

assumes
  cdclW** S S' and
  cdclW-M-level-inv S
shows cdclW-M-level-inv S'
using assms by (induct rule: rtrancpl-induct) (auto intro: cdclW-consistent-inv)
```

lemma *trancpl-cdcl_W-consistent-inv*:

```

assumes
  cdclW++ S S' and
  cdclW-M-level-inv S
shows cdclW-M-level-inv S'
using assms by (induct rule: trancpl-induct) (auto intro: cdclW-consistent-inv)
```

lemma *cdcl_W-M-level-inv-S0-cdcl_W[simp]*:

```

cdclW-M-level-inv (init-state N)
unfolding cdclW-M-level-inv-def by auto
```

lemma *cdcl_W-M-level-inv-get-level-le-backtrack-lvl*:

```

assumes inv: cdclW-M-level-inv S
shows get-level (trail S) L ≤ backtrack-lvl S
using inv unfolding cdclW-M-level-inv-def
by simp
```

lemma *backtrack-ex-decomp*:

```

assumes
  M-l: cdclW-M-level-inv S and
  i-S: i < backtrack-lvl S
shows ∃ K M1 M2. (Decided K # M1, M2) ∈ set (get-all-ann-decomposition (trail S)) ∧
  get-level (trail S) K = Suc i
```

proof –

```

let ?M = trail S
have i < count-decided (trail S)
  using i-S M-l by (auto simp: cdclW-M-level-inv-def)
then obtain c K c' where tr-S: trail S = c @ Decided K # c' and
  lev-K: get-level (trail S) K = Suc i
  using le-count-decided-decomp[of trail S i] M-l by (auto simp: cdclW-M-level-inv-def)
obtain M1 M2 where (Decided K # M1, M2) ∈ set (get-all-ann-decomposition (trail S))
  using Decided-cons-in-get-all-ann-decomposition-append-Decided-cons unfolding tr-S by fast
then show ?thesis using lev-K by blast
qed
```

lemma *backtrack-lvl-backtrack-decrease*:
assumes *inv*: *cdcl_W-M-level-inv S* **and** *bt*: *backtrack S T*
shows *backtrack-lvl T < backtrack-lvl S*
using *inv bt le-count-decided-decomp*[*of trail S backtrack-lvl T*]
unfolding *cdcl_W-M-level-inv-def*
by (*fastforce elim!*: *backtrackE dest!*: *get-all-ann-decomposition-exists-prepend*
simp: *append-assoc*[*of - - # -, symmetric*] *simp del*: *append-assoc*)

Compatibility with $op \sim$

lemma *propagate-state-eq-compatible*:
assumes
propa: *propagate S T* **and**
SS': *S \sim S'* **and**
TT': *T \sim T'*
shows *propagate S' T'*
proof –
obtain *C L* **where**
conf: *conflicting S = None* **and**
C: *C $\in \#$ clauses S* **and**
L: *L $\in \#$ C* **and**
tr: *trail S \models_{as} CNot (remove1-mset L C)* **and**
undef: *undefined-lit (trail S) L* **and**
T: *T \sim cons-trail (Propagated L C) S*
using *propa* **by** (*elim propagateE*) *auto*

have *C'*: *C $\in \#$ clauses S'*
using *SS' C*
by (*auto simp*: *state-eq-def clauses-def simp del*: *state-simp*)

show *?thesis*
apply (*rule propagate-rule*[*of - C*])
using *state-eq-sym*[*of S S'*] *SS' conf C' L tr undef TT' T*
by (*auto simp*: *state-eq-def simp del*: *state-simp*)
qed

lemma *conflict-state-eq-compatible*:
assumes
confl: *conflict S T* **and**
TT': *T \sim T'* **and**
SS': *S \sim S'*
shows *conflict S' T'*
proof –
obtain *D* **where**
conf: *conflicting S = None* **and**
D: *D $\in \#$ clauses S* **and**
tr: *trail S \models_{as} CNot D* **and**
T: *T \sim update-conflicting (Some D) S*
using *confl* **by** (*elim conflictE*) *auto*

have *D'*: *D $\in \#$ clauses S'*
using *D SS'* **by** *fastforce*

show *?thesis*
apply (*rule conflict-rule*[*of - D*])

```

    using state-eq-sym[of S S'] SS' conf D' tr TT' T
    by (auto simp: state-eq-def simp del: state-simp)
qed

lemma backtrack-state-eq-compatible:
  assumes
    bt: backtrack S T and
    SS': S ~ S' and
    TT': T ~ T' and
    inv: cdclW-M-level-inv S
  shows backtrack S' T'
proof -
  obtain D L K i M1 M2 where
    conf: conflicting S = Some D and
    L: L ∈# D and
    decomp: (Decided K # M1, M2) ∈ set (get-all-ann-decomposition (trail S)) and
    lev: get-level (trail S) L = backtrack-lvl S and
    max: get-level (trail S) L = get-maximum-level (trail S) D and
    max-D: get-maximum-level (trail S) (remove1-mset L D) ≡ i and
    lev-K: get-level (trail S) K = Suc i and
    T: T ~ cons-trail (Propagated L D)
    (reduce-trail-to M1
     (add-learned-cls D
      (update-backtrack-lvl i
       (update-conflicting None S))))
  using bt inv by (elim backtrackE) metis
  have D': conflicting S' = Some D
    using SS' conf by (cases conflicting S') auto

  have T': T' ~ cons-trail (Propagated L D)
    (reduce-trail-to M1 (add-learned-cls D
      (update-backtrack-lvl i (update-conflicting None S'))))
  using TT' unfolding state-eq-def
  using decomp D' inv SS' T by (auto simp add: cdclW-M-level-inv-def)

  show ?thesis
  apply (rule backtrack-rule[of - D])
  apply (rule D')
  using state-eq-sym[of S S'] TT' SS' D' conf L decomp lev max max-D T
  apply (auto simp: state-eq-def simp del: state-simp)[]
  using decomp SS' lev SS' max-D max T' lev-K by (auto simp: state-eq-def simp del: state-simp)
qed

lemma decide-state-eq-compatible:
  assumes
    decide S T and
    S ~ S' and
    T ~ T'
  shows decide S' T'
  using assms apply (elim decideE)
  by (rule decide-rule) (auto simp: state-eq-def clauses-def simp del: state-simp)

lemma skip-state-eq-compatible:
  assumes
    skip: skip S T and
    SS': S ~ S' and

```

$TT': T \sim T'$
shows *skip* $S' T'$
proof –
obtain $L C' M E$ **where**
 $tr: \text{trail } S = \text{Propagated } L C' \# M$ **and**
 $raw: \text{conflicting } S = \text{Some } E$ **and**
 $L: -L \notin \# E$ **and**
 $E: E \neq \{\#\}$ **and**
 $T: T \sim \text{tl-trail } S$
using *skip* **by** (*elim skipE*) *simp*
obtain E' **where** $E': \text{conflicting } S' = \text{Some } E'$
using SS' *raw* **by** (*cases conflicting S'*) (*auto simp: state-eq-def simp del: state-simp*)
show ?thesis
apply (*rule skip-rule*)
using tr raw L E T SS' **apply** (*auto simp: simp del:*)[]
using E' **apply** *simp*
using E' SS' L *raw* E **apply** (*auto simp: state-eq-def simp del: state-simp*)[2]
using T TT' SS' **by** (*auto simp: state-eq-def simp del: state-simp*)
qed

lemma *resolve-state-eq-compatible:*

assumes
 $res: \text{resolve } S T$ **and**
 $TT': T \sim T'$ **and**
 $SS': S \sim S'$
shows *resolve* $S' T'$
proof –
obtain $E D L$ **where**
 $tr: \text{trail } S \neq []$ **and**
 $hd: \text{hd-trail } S = \text{Propagated } L E$ **and**
 $L: L \in \# E$ **and**
 $raw: \text{conflicting } S = \text{Some } D$ **and**
 $LD: -L \in \# D$ **and**
 $i: \text{get-maximum-level } (\text{trail } S) ((\text{remove1-mset } (-L) D)) = \text{backtrack-lvl } S$ **and**
 $T: T \sim \text{update-conflicting } (\text{Some } (\text{resolve-cls } L D E)) (\text{tl-trail } S)$
using *assms* **by** (*elim resolveE*) *simp*

obtain D' **where**
 $D': \text{conflicting } S' = \text{Some } D'$
using SS' *raw* **by** *fastforce*
have [*simp*]: $D = D'$
using D' SS' *raw* *state-simp*(5) **by** *fastforce*
have $T'T: T' \sim T$
using TT' *state-eq-sym* **by** *auto*
show ?thesis
apply (*rule resolve-rule*)
using tr SS' **apply** *simp*
using hd SS' **apply** *simp*
using L **apply** *simp*
using D' **apply** *simp*
using D' SS' *raw* LD **apply** (*auto simp add: state-eq-def simp del: state-simp*)[]
using D' SS' *raw* LD **apply** (*auto simp add: state-eq-def simp del: state-simp*)[]
using *raw* SS' i **apply** (*auto simp add: state-eq-def simp del: state-simp*)[]
using T $T'T$ SS' **by** (*auto simp: state-eq-def simp del: state-simp*)
qed

```

lemma forget-state-eq-compatible:
  assumes
    forget: forget S T and
    SS':  $S \sim S'$  and
    TT':  $T \sim T'$ 
  shows forget S' T'
proof –
  obtain C where
    conf: conflicting S = None and
    C:  $C \in \#$  learned-clss S and
    tr:  $\neg(\text{trail } S) \models_{asm} \text{clauses } S$  and
    C1:  $C \notin \text{set } (\text{get-all-mark-of-propagated } (\text{trail } S))$  and
    C2:  $C \notin \#$  init-clss S and
    T:  $T \sim \text{remove-clss } C S$ 
  using forget by (elim forgetE) simp

  show ?thesis
  apply (rule forget-rule)
    using SS' conf apply simp
    using C SS' apply simp
    using SS' tr apply simp
    using SS' C1 apply simp
    using SS' C2 apply simp
    using T TT' SS' by (auto simp: state-eq-def simp del: state-simp)
qed

lemma cdclW-state-eq-compatible:
  assumes
    cdclW S T and  $\neg \text{restart } S T$  and
     $S \sim S'$ 
     $T \sim T'$  and
    cdclW-M-level-inv S
  shows cdclW S' T'
  using assms by (meson backtrack backtrack-state-eq-compatible bj cdclW.simps cdclW-o-rule-cases
    cdclW-rf.cases conflict-state-eq-compatible decide decide-state-eq-compatible forget
    forget-state-eq-compatible propagate-state-eq-compatible resolve resolve-state-eq-compatible
    skip skip-state-eq-compatible state-eq-ref)

lemma cdclW-bj-state-eq-compatible:
  assumes
    cdclW-bj S T and cdclW-M-level-inv S
     $T \sim T'$ 
  shows cdclW-bj S T'
  using assms by (meson backtrack backtrack-state-eq-compatible cdclW-bjE resolve
    resolve-state-eq-compatible skip skip-state-eq-compatible state-eq-ref)

lemma tranclp-cdclW-bj-state-eq-compatible:
  assumes
    cdclW-bj++ S T and inv: cdclW-M-level-inv S and
     $S \sim S'$  and
     $T \sim T'$ 
  shows cdclW-bj++ S' T'
  using assms
proof (induction arbitrary: S' T')
  case base
  then show ?case

```

```

  unfolding tranclp-unfold-end by (meson backtrack-state-eq-compatible cdclW-bj.simps
    resolve-state-eq-compatible rtranclp-unfold skip-state-eq-compatible)
next
case (step T U) note IH = this(3)[OF this(4-5)]
have cdclW++ S T
  using tranclp-mono[of cdclW-bj cdclW] step.hyps(1) cdclW.other cdclW-o.bj by blast
then have cdclW-M-level-inv T
  using inv tranclp-cdclW-consistent-inv by blast
then have cdclW-bj++ T T'
  using ⟨U ~ T'⟩ cdclW-bj-state-eq-compatible[of T U] ⟨cdclW-bj T U⟩ by auto
then show ?case
  using IH[of T] by auto
qed

```

Conservation of some Properties

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) (auto simp: inv 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:*

```

assumes
  cdclW S T and
  inv: cdclW-M-level-inv S
shows init-clss S = init-clss T
using assms by (induction rule: cdclW-all-induct)
(auto simp: inv cdclW-M-level-inv-decomp not-in-iff)

```

lemma *rtranclp-cdcl_W-init-clss:*

```

cdclW** S T  $\implies$  cdclW-M-level-inv S  $\implies$  init-clss S = init-clss T
by (induct rule: rtranclp-induct) (auto dest: cdclW-init-clss rtranclp-cdclW-consistent-inv)

```

lemma *tranclp-cdcl_W-init-clss:*

```

cdclW++ S T  $\implies$  cdclW-M-level-inv S  $\implies$  init-clss S = init-clss T
using rtranclp-cdclW-init-clss[of S T] unfolding rtranclp-unfold by auto

```

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.

definition $cdcl_W$ -learned-clause $(S :: 'st) \longleftrightarrow$
 $(init-clss\ S \models_{psm} learned-clss\ S$
 $\wedge (\forall T. conflicting\ S = Some\ T \longrightarrow init-clss\ S \models_{pm} T)$
 $\wedge set\ (get-all-mark-of-propagated\ (trail\ S)) \subseteq set-mset\ (clauses\ S))$

of Weidenbach's book for the initial state and some additional structural properties about the trail.

lemma $cdcl_W$ -learned-clause-S0- $cdcl_W[simp]$:
 $cdcl_W$ -learned-clause $(init-state\ N)$
unfolding $cdcl_W$ -learned-clause-def **by** auto

Item 4 page 81 of Weidenbach's book

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)
case (backtrack $K\ i\ M1\ M2\ L\ D\ T$) **note** $decomp = this(3)$ **and** $confl = this(1)$ **and** $lev-K = this(7)$ **and**
 $undef = this(8)$ **and** $T = this(9)$
show ?case
using $decomp\ confl\ learned\ undef\ T\ lev-K$ **unfolding** $cdcl_W$ -learned-clause-def
by (auto dest!: get-all-ann-decomposition-exists-prepend
 $simp: clauses-def\ lev-inv\ cdcl_W$ -M-level-inv-decomp dest: true-clss-clss-left-right)
next
case (resolve $L\ C\ M\ D$) **note** $trail = this(1)$ **and** $CL = this(2)$ **and** $confl = this(4)$ **and** $DL = this(5)$
and $lvl = this(6)$ **and** $T = this(7)$
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)
moreover have $remove1-mset\ (-\ L)\ D + \{\#-\ L\#\} = D$
using DL **by** (auto simp: multiset-eq-iff)
moreover have $remove1-mset\ L\ C + \{\#L\#\} = C$
using CL **by** (auto simp: multiset-eq-iff)
ultimately show ?case
using $learned\ T$
by (auto dest: mk-disjoint-insert
 $simp\ add: cdcl_W$ -learned-clause-def $clauses-def$
 $intro!: true-clss-clss-union-mset-true-clss-clss-or-not-true-clss-clss-or[of\ -\ -\ L])$


```

next
  case (restart T)
  then show ?case
    using learned
    by (auto
      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)
next
  case conflict
  then show ?case using learned
    by (fastforce simp: cdclW-learned-clause-def clauses-def
      true-clss-clss-in-imp-true-clss-clss)
next
  case (forget U)
  then show ?case using learned
    by (auto simp: cdclW-learned-clause-def clauses-def split: if-split-asm)
qed (auto simp: cdclW-learned-clause-def clauses-def)

lemma rtranclp-cdclW-learned-clss:
  assumes
    cdclW** S S' and
    cdclW-M-level-inv S
    cdclW-learned-clause S
  shows cdclW-learned-clause S'
  using assms by induction (auto dest: cdclW-learned-clss intro: rtranclp-cdclW-consistent-inv)

```

No alien atom in the state

This invariant means that all the literals are in the set of clauses. These properties are implicit in Weidenbach's book.

definition *no-strange-atm* $S' \longleftrightarrow$ (
 $(\forall T. \text{conflicting } S' = \text{Some } T \longrightarrow \text{atms-of } T \subseteq \text{atms-of-mm } (\text{init-clss } S'))$
 $\wedge (\forall L \text{ mark. } \text{Propagated } L \text{ mark} \in \text{set } (\text{trail } S') \longrightarrow \text{atms-of mark} \subseteq \text{atms-of-mm } (\text{init-clss } S'))$
 $\wedge \text{atms-of-mm } (\text{learned-clss } S') \subseteq \text{atms-of-mm } (\text{init-clss } S')$
 $\wedge \text{atm-of } ' (\text{lits-of-l } (\text{trail } S')) \subseteq \text{atms-of-mm } (\text{init-clss } S')$)

lemma *no-strange-atm-decomp*:
 assumes *no-strange-atm* S
 shows *conflicting* S = *Some* T $\implies \text{atms-of } T \subseteq \text{atms-of-mm } (\text{init-clss } S)$
 and $(\forall L \text{ mark. } \text{Propagated } L \text{ mark} \in \text{set } (\text{trail } S) \longrightarrow \text{atms-of mark} \subseteq \text{atms-of-mm } (\text{init-clss } S))$
 and $\text{atms-of-mm } (\text{learned-clss } S) \subseteq \text{atms-of-mm } (\text{init-clss } S)$
 and $\text{atm-of } ' (\text{lits-of-l } (\text{trail } S)) \subseteq \text{atms-of-mm } (\text{init-clss } S)$
 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 *in-atms-of-implies-atm-of-on-atms-of-ms*:
 $C + \{\#L\# \} \in \# A \implies x \in \text{atms-of } C \implies x \in \text{atms-of-mm } A$

using *multi-member-split* **by** *fastforce*

lemma *propagate-no-strange-atm-inv*:

assumes

propagate S T and

alien: no-strange-atm S

shows *no-strange-atm T*

using *assms(1)*

proof (*induction*)

case (*propagate-rule C L T*) **note** *confl = this(1) and C = this(2) and C-L = this(3) and*

tr = this(4) and undef = this(5) and T = this(6)

have *atm-CL: atms-of C ⊆ atms-of-mm (init-clss S)*

using *C alien unfolding no-strange-atm-def*

by (*auto simp: clauses-def atms-of-ms-def*)

show *?case*

unfolding *no-strange-atm-def*

proof (*intro conjI allI impI, goal-cases*)

case 1

then show *?case*

using *confl T undef by auto*

next

case (*2 L' mark'*)

then show *?case*

using *C-L T alien undef atm-CL unfolding no-strange-atm-def clauses-def by (auto 5 5)*

next

case (*3*)

show *?case using T alien undef unfolding no-strange-atm-def by auto*

next

case (*4*)

show *?case*

using *T alien undef C-L atm-CL unfolding no-strange-atm-def by (auto simp: atms-of-def)*

qed

qed

lemma *in-atms-of-remove1-mset-in-atms-of*:

$x \in \text{atms-of } (\text{remove1-mset } L \ C) \implies x \in \text{atms-of } C$

using *in-diffD unfolding atms-of-def by fastforce*

lemma *atms-of-ms-learned-clss-restart-state-in-atms-of-ms-learned-clssI*:

$\text{atms-of-mm } (\text{learned-clss } S) \subseteq \text{atms-of-mm } (\text{init-clss } S) \implies$

$x \in \text{atms-of-mm } (\text{learned-clss } T) \implies$

$\text{learned-clss } T \subseteq \# \text{ learned-clss } S \implies$

$x \in \text{atms-of-mm } (\text{init-clss } S)$

by (*meson atms-of-ms-mono contra-subsetD set-mset-mono*)

lemma *cdcl_W-no-strange-atm-explicit*:

assumes

cdcl_W S S' and

lev: cdcl_W-M-level-inv S and

conf: ∀ T. conflicting S = Some T ⟶ atms-of T ⊆ atms-of-mm (init-clss S) and

decided: ∀ L mark. Propagated L mark ∈ set (trail S)

$\implies \text{atms-of mark} \subseteq \text{atms-of-mm } (\text{init-clss } S)$ **and**

learned: atms-of-mm (learned-clss S) ⊆ atms-of-mm (init-clss S) and

trail: atm-of ' (lits-of-l (trail S)) ⊆ atms-of-mm (init-clss S)

shows

$(\forall T. \text{conflicting } S' = \text{Some } T \implies \text{atms-of } T \subseteq \text{atms-of-mm } (\text{init-clss } S')) \wedge$

```

(∀ L mark. Propagated L mark ∈ set (trail S')
  → atms-of mark ⊆ atms-of-mm (init-clss S') ∧
  atms-of-mm (learned-clss S') ⊆ atms-of-mm (init-clss S') ∧
  atm-of ' (lits-of-l (trail S')) ⊆ atms-of-mm (init-clss S')
  (is ?C S' ∧ ?M S' ∧ ?U S' ∧ ?V S'))
using assms(1,2)
proof (induct rule: cdclW-all-induct)
  case (propagate C L T) note confl = this(1) and C-L = this(2) and tr = this(3) and undef =
  this(4)
  and T = this(5)
  show ?case
    using propagate-rule[OF propagate.hyps(1-3) - propagate.hyps(5,6), simplified]
    propagate.hyps(4) propagate-no-strange-atm-inv[of S T]
    conf decided learned trail unfolding no-strange-atm-def by presburger
next
  case (decide L)
  then show ?case using learned decided conf trail unfolding clauses-def by auto
next
  case (skip L C M D)
  then show ?case using learned decided conf trail by auto
next
  case (conflict D T) note D-S = this(2) and T = this(4)
  have D: atm-of ' set-mset D ⊆ ⋃ (atms-of ' (set-mset (clauses S)))
    using D-S by (auto simp add: atms-of-def atms-of-ms-def)
  moreover {
    fix xa :: 'v literal
    assume a1: atm-of ' set-mset D ⊆ (⋃ x∈set-mset (init-clss S). atms-of x)
      ∪ (⋃ x∈set-mset (learned-clss S). atms-of x)
    assume a2:
      (⋃ x∈set-mset (learned-clss S). atms-of x) ⊆ (⋃ x∈set-mset (init-clss S). atms-of x)
    assume xa ∈# D
    then have atm-of xa ∈ UNION (set-mset (init-clss S)) atms-of
      using a2 a1 by (metis (no-types) Un-iff atm-of-lit-in-atms-of atms-of-def subset-Un-eq)
    then have ∃ m∈set-mset (init-clss S). atm-of xa ∈ atms-of m
      by blast
  } note H = this
  ultimately show ?case using conflict.premis T learned decided conf trail
  unfolding atms-of-def atms-of-ms-def clauses-def
  by (auto simp add: H)
next
  case (restart T)
  then show ?case using learned decided conf trail
  by (auto intro: atms-of-ms-learned-clss-restart-state-in-atms-of-ms-learned-clssI)
next
  case (forget C T) note confl = this(1) and C = this(4) and C-le = this(5) and
  T = this(6)
  have H: ∧ L mark. Propagated L mark ∈ set (trail S) ⇒ atms-of mark ⊆ atms-of-mm (init-clss S)
  using decided by simp
  show ?case unfolding clauses-def apply (intro conjI)
    using conf confl T trail C unfolding clauses-def apply (auto dest!: H)[]
    using T trail C C-le apply (auto dest!: H)[]
    using T learned C-le atms-of-ms-remove-subset[of set-mset (learned-clss S)] apply auto[]
    using T trail C-le apply (auto simp: clauses-def lits-of-def)[]
  done
next
  case (backtrack L D K i M1 M2 T) note confl = this(1) and LD = this(2) and decomp = this(3)

```

and
 $lev-K = this(7)$ **and** $T = this(8)$
have $?C\ T$
using $conf\ T\ decomp\ lev\ lev-K$ **by** $(auto\ simp: cdcl_W-M-level-inv-decomp)$
moreover have $set\ M1 \subseteq set\ (trail\ S)$
using $decomp$ **by** $auto$
then have $M: ?M\ T$
using $decided\ conf\ confl\ T\ decomp\ lev\ lev-K$
by $(auto\ simp: image-subset-iff\ clauses-def\ cdcl_W-M-level-inv-decomp)$
moreover have $?U\ T$
using $learned\ decomp\ conf\ confl\ T\ lev\ lev-K$ **unfolding** $clauses-def$
by $(auto\ simp: cdcl_W-M-level-inv-decomp)$
moreover have $?V\ T$
using $M\ conf\ confl\ trail\ T\ decomp\ lev\ LD\ lev-K$
by $(auto\ simp: cdcl_W-M-level-inv-decomp\ atms-of-def\ dest!: get-all-ann-decomposition-exists-prepend)$
ultimately show $?case$ **by** $blast$
next
case $(resolve\ L\ C\ M\ D\ T)$ **note** $trail-S = this(1)$ **and** $confl = this(4)$ **and** $T = this(7)$
let $?T = update-conflicting\ (Some\ (resolve-cls\ L\ D\ C))\ (tl-trail\ S)$
have $?C\ ?T$
using $confl\ trail-S\ conf\ decided$ **by** $(auto\ dest!: in-atms-of-remove1-mset-in-atms-of)$
moreover have $?M\ ?T$
using $confl\ trail-S\ conf\ decided$ **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** $simp$
qed

lemma $cdcl_W-no-strange-atm-inv$:
assumes $cdcl_W\ S\ S'$ **and** $no-strange-atm\ S$ **and** $cdcl_W-M-level-inv\ S$
shows $no-strange-atm\ S'$
using $cdcl_W-no-strange-atm-explicit[OF\ assms(1)]\ assms(2,3)$ **unfolding** $no-strange-atm-def$ **by** $fast$

lemma $rtranclp-cdcl_W-no-strange-atm-inv$:
assumes $cdcl_W^{**}\ S\ S'$ **and** $no-strange-atm\ S$ **and** $cdcl_W-M-level-inv\ S$
shows $no-strange-atm\ S'$
using $assms$ **by** $induction\ (auto\ intro: cdcl_W-no-strange-atm-inv\ rtranclp-cdcl_W-consistent-inv)$

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 also. Remark that we will show later that there cannot be duplicate *clause*.

definition $distinct-cdcl_W-state\ (S :: 'st)$
 $\longleftrightarrow ((\forall\ T.\ conflicting\ S = Some\ T \longrightarrow distinct-mset\ T)$
 $\wedge\ distinct-mset-mset\ (learned-clss\ S)$
 $\wedge\ distinct-mset-mset\ (init-clss\ S)$
 $\wedge\ (\forall\ L\ mark.\ (Propagated\ L\ mark \in set\ (trail\ S) \longrightarrow distinct-mset\ mark)))$

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**
 $\text{distinct-mset-mset } (\text{learned-clss } S)$ **and**
 $\text{distinct-mset-mset } (\text{init-clss } S)$ **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*) **and** *conflicting* *S = Some T*
shows *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
 $\text{cdcl}_W \ S \ S'$ **and**
 $\text{lev-inv: cdcl}_W\text{-M-level-inv } S$ **and**
 $\text{distinct-cdcl}_W\text{-state } S$
shows $\text{distinct-cdcl}_W\text{-state } S'$
using *assms*(1,2,2,3)
proof (*induct* rule: *cdcl_W-all-induct*)
case (*backtrack L D K i M1 M2*)
then show *?case*
using *lev-inv* **unfolding** *distinct-cdcl_W-state-def*
by (*auto* *dest: get-all-ann-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* **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: distinct-cdcl_W-state-def distinct-mset-set-def clauses-def*
 $\text{dest!}: \text{in-diffD}$)

lemma *rtanclp-distinct-cdcl_W-state-inv*:
assumes
 $\text{cdcl}_W^{**} \ S \ S'$ **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* **apply** (*induct* rule: *rtanclp-induct*)
using *distinct-cdcl_W-state-inv rtanclp-cdcl_W-consistent-inv* **by** *blast+*

Conflicts and Annotations

This invariant shows that each mark contains a contradiction only related to the previously defined variable.

abbreviation *every-mark-is-a-conflict :: 'st \Rightarrow bool* **where**
every-mark-is-a-conflict *S* \equiv

$\forall L \text{ mark } a \text{ b. } a @ \text{ Propagated } L \text{ mark } \# \text{ b} = (\text{trail } S) \\ \longrightarrow (b \models_{as} \text{CNot } (\text{mark} - \{\#L\}) \wedge L \in \# \text{ mark})$

definition $\text{cdcl}_W\text{-conflicting } S \longleftrightarrow \\ (\forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{trail } S \models_{as} \text{CNot } T) \\ \wedge \text{every-mark-is-a-conflict } S$

lemma $\text{backtrack-atms-of-}D\text{-in-}M1$:

fixes $M1 :: ('v, 'v \text{ clause}) \text{ ann-lits}$

assumes

$\text{inv: cdcl}_W\text{-}M\text{-level-inv } S \text{ and}$

$i: \text{get-maximum-level } (\text{trail } S) ((\text{remove1-mset } L \ D)) \equiv i \text{ and}$

$\text{decomp: (Decided } K \ \# \ M1, \ M2)$

$\in \text{set } (\text{get-all-ann-decomposition } (\text{trail } S)) \text{ and}$

$S\text{-lvl: backtrack-lvl } S = \text{get-maximum-level } (\text{trail } S) \ D \text{ and}$

$S\text{-confl: conflicting } S = \text{Some } D \text{ and}$

$\text{lev-}K: \text{get-level } (\text{trail } S) \ K = \text{Suc } i \text{ and}$

$T: T \sim \text{cons-trail } (\text{Propagated } L \ D)$

$(\text{reduce-trail-to } M1$

$(\text{add-learned-cls } D$

$(\text{update-backtrack-lvl } i$

$(\text{update-conflicting } \text{None } S)))) \text{ and}$

$\text{confl: } \forall T. \text{conflicting } S = \text{Some } T \longrightarrow \text{trail } S \models_{as} \text{CNot } T$

shows $\text{atms-of } ((\text{remove1-mset } L \ D)) \subseteq \text{atm-of } ' \text{ lits-of-l } (\text{tl } (\text{trail } T))$

proof (rule ccontr)

let $?k = \text{get-maximum-level } (\text{trail } S) \ D$

let $?D' = \text{remove1-mset } L \ D$

have $\text{trail } S \models_{as} \text{CNot } D \text{ using } \text{confl } S\text{-confl} \text{ by } \text{auto}$

then have $\text{vars-of-}D: \text{atms-of } D \subseteq \text{atm-of } ' \text{ lits-of-l } (\text{trail } S) \text{ unfolding } \text{atms-of-def} \\ \text{by } (\text{meson image-subsetI true-annots-CNot-all-atms-defined})$

obtain $M0 \text{ where } M: \text{trail } S = M0 @ M2 @ \text{Decided } K \ \# \ M1$

using $\text{decomp} \text{ by } \text{auto}$

have $\text{max: } ?k = \text{count-decided } (M0 @ M2 @ \text{Decided } K \ \# \ M1)$

using $\text{inv} \text{ unfolding } \text{cdcl}_W\text{-}M\text{-level-inv-def } S\text{-lvl } M \text{ by } \text{simp}$

assume $a: \neg ?thesis$

then obtain $L' \text{ where}$

$L': L' \in \text{atms-of } ?D' \text{ and}$

$L'\text{-notin-}M1: L' \notin \text{atm-of } ' \text{ lits-of-l } M1$

using $T \text{ decomp inv by } (\text{auto simp: cdcl}_W\text{-}M\text{-level-inv-decomp})$

then have $L'\text{-in: } L' \in \text{atm-of } ' \text{ lits-of-l } (M0 @ M2 @ \text{Decided } K \ \# \ [])$

using $\text{vars-of-}D \text{ unfolding } M \text{ by } (\text{auto dest: in-atms-of-remove1-mset-in-atms-of})$

then obtain $L'' \text{ where}$

$L'' \in \# \ ?D' \text{ and}$

$L'': L' = \text{atm-of } L''$

using $L' \ L'\text{-notin-}M1 \text{ unfolding } \text{atms-of-def} \text{ by } \text{auto}$

have $\text{atm-of } K \notin \text{atm-of } ' \text{ lits-of-l } (M0 @ M2)$

using $\text{inv} \text{ by } (\text{auto simp: cdcl}_W\text{-}M\text{-level-inv-def } M \text{ lits-of-def})$

then have $\text{count-decided } M1 = i$

using $\text{lev-}K \text{ unfolding } M \text{ by } (\text{auto simp: image-Un})$

then have $\text{lev-}L'':$

$\text{get-level } (\text{trail } S) \ L'' = \text{get-level } (M0 @ M2 @ \text{Decided } K \ \# \ []) \ L'' + i$

using $L'\text{-notin-}M1 \ L'' \text{ get-rev-level-skip-end[OF } L'\text{-in[unfolded } L''], \text{ of } M1] \ M \text{ by } \text{auto}$

moreover

consider

```

(M0)  $L' \in \text{atm-of } \text{'lits-of-l } M0 \mid$ 
(M2)  $L' \in \text{atm-of } \text{'lits-of-l } M2 \mid$ 
(K)  $L' = \text{atm-of } K$ 
using inv  $L'$ -in unfolding  $L''$  by (auto simp: cdclW-M-level-inv-def)
then have get-level ( $M0 @ M2 @ \text{Decided } K \# []$ )  $L'' \geq \text{Suc } 0$ 
proof cases
  case  $M0$ 
  then have  $L' \neq \text{atm-of } K$ 
  using inv  $\langle \text{atm-of } K \notin \text{atm-of } \text{'lits-of-l } (M0 @ M2) \rangle$  unfolding  $L''$  by auto
  then show ?thesis using  $M0$  unfolding  $L''$  by auto
next
  case  $M2$ 
  then have  $L' \notin \text{atm-of } \text{'lits-of-l } (M0 @ \text{Decided } K \# [])$ 
  using inv  $\langle \text{atm-of } K \notin \text{atm-of } \text{'lits-of-l } (M0 @ M2) \rangle$  unfolding  $L''$ 
  by (auto simp: M cdclW-M-level-inv-def atm-lit-of-set-lits-of-l)
  then show ?thesis using  $M2$  unfolding  $L''$  by (auto simp: image-Un)
next
  case  $K$ 
  then have  $L' \notin \text{atm-of } \text{'lits-of-l } (M0 @ M2)$ 
  using inv unfolding  $L''$  by (auto simp: cdclW-M-level-inv-def atm-lit-of-set-lits-of-l M)
  then show ?thesis using  $K$  unfolding  $L''$  by (auto simp: image-Un)
qed
ultimately have get-level (trail S)  $L'' \geq i + 1$ 
using lev-L'' unfolding  $M$  by simp
then have get-maximum-level (trail S)  $?D' \geq i + 1$ 
using get-maximum-level-ge-get-level[OF  $\langle L'' \in \# ?D' \rangle$ , of trail S] by auto
then show False using  $i$  by auto
qed

```

lemma *distinct-atms-of-incl-not-in-other:*

```

assumes
  a1: no-dup ( $M @ M'$ ) and
  a2: atms-of  $D \subseteq \text{atm-of } \text{'lits-of-l } M'$  and
  a3:  $x \in \text{atms-of } D$ 
shows  $x \notin \text{atm-of } \text{'lits-of-l } M$ 
proof –
  have ff1:  $\bigwedge l \text{ ms. } \text{undefined-lit } ms \ l \vee \text{atm-of } l$ 
     $\in \text{set } (\text{map } (\lambda m. \text{atm-of } (\text{lit-of } (m :: ('a, 'b) \text{ ann-lit}))) \text{ ms})$ 
    by (simp add: defined-lit-map)
  have ff2:  $\bigwedge a. a \notin \text{atms-of } D \vee a \in \text{atm-of } \text{'lits-of-l } M'$ 
    using  $a2$  by (meson subsetCE)
  have ff3:  $\bigwedge a. a \notin \text{set } (\text{map } (\lambda m. \text{atm-of } (\text{lit-of } m)) M')$ 
     $\vee a \notin \text{set } (\text{map } (\lambda m. \text{atm-of } (\text{lit-of } m)) M)$ 
    using  $a1$  by (metis (lifting) IntI distinct-append empty-iff map-append)
  have  $\forall L \ a \ f. \exists l. ((a :: 'a) \notin f \text{' } L \vee (l :: 'a \text{ literal}) \in L) \wedge (a \notin f \text{' } L \vee f \ l = a)$ 
    by blast
  then show  $x \notin \text{atm-of } \text{'lits-of-l } M$ 
    using ff3 ff2 ff1 a3 by (metis (no-types) Decided-Propagated-in-iff-in-lits-of-l)
qed

```

Item 5 page 81 of Weidenbach's book

lemma *cdcl_W-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-ann-decomposition (trail S)) and

```

```

  learned: cdclW-learned-clause 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
shows all-decomposition-implies-m (init-clss S') (get-all-ann-decomposition (trail S'))
using assms(1,2)
proof (induct rule: cdclW-all-induct)
  case restart
  then show ?case by auto
next
  case forget
  then show ?case using decomp by auto
next
  case conflict
  then show ?case using decomp by auto
next
  case (resolve L C M D) note tr = this(1) and T = this(7)
  let ?decomp = get-all-ann-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-ann-decomposition M))
      (auto simp: M)
next
  case (skip L C' M D) note tr = this(1) and T = this(5)
  have M: set (get-all-ann-decomposition M)
    = insert (hd (get-all-ann-decomposition M)) (set (tl (get-all-ann-decomposition M)))
    by (cases get-all-ann-decomposition M) auto
  show ?case
    using decomp tr T unfolding all-decomposition-implies-def
    by (cases hd (get-all-ann-decomposition M))
      (auto simp add: M)
next
  case decide note S = this(1) and undef = this(2) and T = this(4)
  show ?case using decomp T undef unfolding S all-decomposition-implies-def by auto
next
  case (propagate C L T) note propa = this(2) and L = this(3) and undef = this(5) and T = this(6)
  obtain a y where ay: hd (get-all-ann-decomposition (trail S)) = (a, y)
    by (cases hd (get-all-ann-decomposition (trail S)))
  then have M: trail S = y @ a using get-all-ann-decomposition-decomp by blast
  have M': set (get-all-ann-decomposition (trail S))
    = insert (a, y) (set (tl (get-all-ann-decomposition (trail S))))
    using ay by (cases get-all-ann-decomposition (trail S)) auto
  have unmark-l a  $\cup$  set-mset (init-clss S)  $\models_{\text{ps}}$  unmark-l y
    using decomp ay unfolding all-decomposition-implies-def
    by (cases get-all-ann-decomposition (trail S)) fastforce+
  then have a-Un-N-M: unmark-l a  $\cup$  set-mset (init-clss S)
     $\models_{\text{ps}}$  unmark-l (trail S)
    unfolding M by (auto simp add: all-in-true-clss-clss image-Un)

  have unmark-l a  $\cup$  set-mset (init-clss S)  $\models_p$  {#L#} (is ?I  $\models_p$  -)
  proof (rule true-clss-clss-plus-CNot)
    show ?I  $\models_p$  remove1-mset L C + {#L#}
    apply (rule true-clss-clss-in-imp-true-clss-clss[of -
      set-mset (init-clss S)  $\cup$  set-mset (learned-clss S)])
    using learned propa L by (auto simp: clauses-def cdclW-learned-clause-def

```



```

      true-annot-CNot-diff)
next
  have unmark-l (trail S)  $\models_{ps}$  CNot (remove1-mset L C)
    using  $\langle (trail S) \models_{as} CNot (remove1-mset L C) \rangle$  true-annots-true-clss-clss
    by blast
  then show ?I  $\models_{ps}$  CNot (remove1-mset L C)
    using a-Un-N-M true-clss-clss-left-right true-clss-clss-union-l-r by blast
qed
moreover have  $\bigwedge aa b.$ 
   $\forall (Ls, seen) \in set (get-all-ann-decomposition (y @ a)).$ 
   $unmark-l Ls \cup set-mset (init-clss S) \models_{ps} unmark-l seen \implies$ 
   $(aa, b) \in set (tl (get-all-ann-decomposition (y @ a))) \implies$ 
   $unmark-l aa \cup set-mset (init-clss S) \models_{ps} unmark-l b$ 
by (metis (no-types, lifting) case-prod-conv get-all-ann-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  $\langle unmark-l a \cup set-mset (init-clss S) \models_{ps} unmark-l y \rangle$ 
  ay by auto
next
  case (backtrack L D K i M1 M2 T) note conf = this(1) and LD = this(2) and decomp' = this(3)
and
  lev-L = this(4) and lev-K = this(7) and undef = this(8) and T = this(9)
let ?D' = remove1-mset L D
have  $\forall l \in set M2. \neg is-decided l$ 
  using get-all-ann-decomposition-snd-not-decided decomp' by blast
obtain M0 where M: trail S = M0 @ M2 @ Decided K # M1
  using decomp' by auto
show ?case unfolding all-decomposition-implies-def
proof
  fix x
  assume  $x \in set (get-all-ann-decomposition (trail T))$ 
  then have x:  $x \in set (get-all-ann-decomposition (Propagated L D \# M1))$ 
    using T decomp' undef inv by (simp add: cdclW-M-level-inv-decomp)
  let ?m = get-all-ann-decomposition (Propagated L D \# M1)
  let ?hd = hd ?m
  let ?tl = tl ?m
  consider
    (hd)  $x = ?hd$ 
  | (tl)  $x \in set ?tl$ 
  using x by (cases ?m) auto
  then show case x of (Ls, seen)  $\Rightarrow unmark-l Ls \cup set-mset (init-clss T) \models_{ps} unmark-l seen$ 
  proof cases
    case tl
    then have  $x \in set (get-all-ann-decomposition (trail S))$ 
      using tl-get-all-ann-decomposition-skip-some[of x] by (simp add: list.set-sel(2) M)
    then show ?thesis
      using decomp learned decomp confl alien inv T undef M
      unfolding all-decomposition-implies-def cdclW-M-level-inv-def
      by auto
  next
    case hd
    obtain M1' M1'' where M1:  $hd (get-all-ann-decomposition M1) = (M1', M1'')$ 
      by (cases hd (get-all-ann-decomposition M1))
    then have x':  $x = (M1', Propagated L D \# M1'')$ 

```

```

    using ⟨x = ?hd⟩ by auto
  have (M1', M1'') ∈ set (get-all-ann-decomposition (trail S))
    using M1[symmetric] hd-get-all-ann-decomposition-skip-some[OF M1[symmetric],
      of M0 @ M2] unfolding M by fastforce
  then have 1: unmark-l M1' ∪ set-mset (init-clss S) ⊨ps unmark-l M1''
    using decomp unfolding all-decomposition-implies-def by auto

  moreover
  have vars-of-D: atms-of ?D' ⊆ atm-of ' lits-of-l M1
    using backtrack-atms-of-D-in-M1[of S D L i K M1 M2 T] backtrack.hyps 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:
    ∀ x ∈ atms-of ?D'. x ∉ atm-of ' lits-of-l (M0 @ M2 @ Decided K # [])
    using vars-of-D distinct-atms-of-incl-not-in-other[of
      M0 @ M2 @ Decided K # [] M1] unfolding M by auto
  have trail S ⊨as CNot (remove1-mset L D)
    using conf confl LD unfolding M true-annots-true-clss-def-iff-negation-in-model
    by (auto dest!: Multiset.in-diffD)
  then have M1 ⊨as CNot ?D'
    using vars-in-M1 true-annots-remove-if-notin-vars[of M0 @ M2 @ Decided K # []
      M1 CNot ?D'] conf confl unfolding M lits-of-def by simp
  have M1 = M1'' @ M1' by (simp add: M1 get-all-ann-decomposition-decomp)
  have TT: unmark-l M1' ∪ set-mset (init-clss S) ⊨ps CNot ?D'
    using true-annots-true-clss-clss[OF ⟨M1 ⊨as CNot ?D'⟩] true-clss-clss-left-right[OF 1]
    unfolding ⟨M1 = M1'' @ M1'⟩ by (auto simp add: inf-sup-aci(5,7))
  have init-clss S ⊨pm ?D' + {#L#}
    using conf learned confl LD unfolding cdclW-learned-clause-def by auto
  then have T': unmark-l M1' ∪ set-mset (init-clss S) ⊨p ?D' + {#L#} by auto
  have atms-of (?D' + {#L#}) ⊆ atms-of-mm (clauses S)
    using alien conf LD unfolding no-strange-atm-def clauses-def by auto
  then have unmark-l M1' ∪ set-mset (init-clss S) ⊨p {#L#}
    using true-clss-clss-plus-CNot[OF T' TT] by auto

  ultimately show ?thesis
    using T' T decomp' undef inv unfolding x' by (simp add: cdclW-M-level-inv-decomp)
qed
qed
qed

```

lemma *cdcl_W-propagate-is-false:*

```

  assumes
    cdclW S S' and
    lev: cdclW-M-level-inv S and
    learned: cdclW-learned-clause S and
    decomp: all-decomposition-implies-m (init-clss S) (get-all-ann-decomposition (trail S)) and
    confl: ∀ T. conflicting S = Some T ⟶ trail S ⊨as CNot T and
    alien: no-strange-atm S and
    mark-confl: every-mark-is-a-conflict S
  shows every-mark-is-a-conflict S'
  using assms(1,2)
proof (induct rule: cdclW-all-induct)
  case (propagate C L T) note LC = this(3) and confl = this(4) and undef = this(5) and T =
  this(6)
  show ?case
    proof (intro allI impI)

```

```

    fix  $L'$  mark  $a$   $b$ 
    assume  $a @ \text{Propagated } L' \text{ mark } \# b = \text{trail } T$ 
    then consider
      ( $hd$ )  $a = []$  and  $L = L'$  and  $\text{mark} = C$  and  $b = \text{trail } S$ 
      | ( $tl$ )  $tl \ a @ \text{Propagated } L' \text{ mark } \# b = \text{trail } S$ 
      using  $T \text{ undef by (cases } a) \text{ fastforce+}$ 
    then show  $b \models_{as} CNot (\text{mark} - \{\#L'\# \}) \wedge L' \in \# \text{ mark}$ 
      using  $\text{mark-confli confl } LC \text{ by cases auto}$ 
    qed
  next
  case ( $decide \ L$ ) note  $\text{undef[simp]} = \text{this}(2)$  and  $T = \text{this}(4)$ 
  have  $\bigwedge a \ La \ \text{mark } b. a @ \text{Propagated } La \ \text{mark } \# b = \text{Decided } L \ \# \text{trail } S$ 
     $\implies tl \ a @ \text{Propagated } La \ \text{mark } \# b = \text{trail } S \text{ by (case-tac } a) \text{ auto}$ 
  then show  $?case$  using  $\text{mark-confli } T \text{ unfolding decide.hyps}(1) \text{ by fastforce}$ 
next
  case ( $skip \ L \ C' \ M \ D \ T$ ) note  $tr = \text{this}(1)$  and  $T = \text{this}(5)$ 
  show  $?case$ 
  proof (intro allI impI)
    fix  $L'$  mark  $a$   $b$ 
    assume  $a @ \text{Propagated } L' \text{ mark } \# b = \text{trail } T$ 
    then have  $a @ \text{Propagated } L' \text{ mark } \# b = M$  using  $tr \ T \text{ by simp}$ 
    then have  $(\text{Propagated } L \ C' \ \# a) @ \text{Propagated } L' \text{ mark } \# b = \text{Propagated } L \ C' \ \# M$  by auto
    moreover have  $\forall La \ \text{mark } a \ b. a @ \text{Propagated } La \ \text{mark } \# b = \text{Propagated } L \ C' \ \# M$ 
       $\longrightarrow b \models_{as} CNot (\text{mark} - \{\#La\# \}) \wedge La \in \# \text{ mark}$ 
      using  $\text{mark-confli unfolding skip.hyps}(1) \text{ by simp}$ 
    ultimately show  $b \models_{as} CNot (\text{mark} - \{\#L'\# \}) \wedge L' \in \# \text{ mark}$  by blast
  qed
next
  case ( $conflict \ D$ )
  then show  $?case$  using  $\text{mark-confli by simp}$ 
next
  case ( $resolve \ L \ C \ M \ D \ T$ ) note  $tr-S = \text{this}(1)$  and  $T = \text{this}(7)$ 
  show  $?case$  unfolding  $\text{resolve.hyps}(1)$ 
  proof (intro allI impI)
    fix  $L'$  mark  $a$   $b$ 
    assume  $a @ \text{Propagated } L' \text{ mark } \# b = \text{trail } T$ 
    then have  $(\text{Propagated } L \ (C + \{\#L'\# \}) \ \# a) @ \text{Propagated } L' \text{ mark } \# b$ 
       $= \text{Propagated } L \ (C + \{\#L'\# \}) \ \# M$ 
      using  $T \ tr-S \text{ by auto}$ 
    then show  $b \models_{as} CNot (\text{mark} - \{\#L'\# \}) \wedge L' \in \# \text{ mark}$ 
      using  $\text{mark-confli unfolding tr-S by (metis Cons-eq-appendI list.sel}(3))$ 
  qed
next
  case restart
  then show  $?case$  by auto
next
  case forget
  then show  $?case$  using  $\text{mark-confli by auto}$ 
next
  case ( $backtrack \ L \ D \ K \ i \ M1 \ M2 \ T$ ) note  $\text{conf} = \text{this}(1)$  and  $LD = \text{this}(2)$  and  $\text{decomp} = \text{this}(3)$ 
  and
     $lev-K = \text{this}(7)$  and  $T = \text{this}(8)$ 
  have  $\forall l \in \text{set } M2. \neg \text{is-decided } l$ 
    using  $\text{get-all-ann-decomposition-snd-not-decided decomp by blast}$ 
  obtain  $M0$  where  $M: \text{trail } S = M0 @ M2 @ \text{Decided } K \ \# M1$ 
    using  $\text{decomp by auto}$ 

```

```

have [simp]: trail (reduce-trail-to M1 (add-learned-cls D
  (update-backtrack-lvl i (update-conflicting None S)))) = M1
  using decomp lev by (auto simp: cdclW-M-level-inv-decomp)
let ?D' = remove1-mset L D
show ?case
proof (intro allI impI)
  fix La :: 'v literal and mark :: 'v clause and
    a b :: ('v, 'v clause) ann-lits
  assume a @ Propagated La mark # b = trail T
  then consider
    (hd-tr) a = [] and
      (Propagated La mark :: ('v, 'v clause) ann-lit) = Propagated L D and
      b = M1
  | (tl-tr) tl a @ Propagated La mark # b = M1
  using M T decomp lev by (cases a) (auto simp: cdclW-M-level-inv-def)
then show b ⊨as CNot (mark - {#La#}) ∧ La ∈# mark
proof cases
  case hd-tr note A = this(1) and P = this(2) and b = this(3)
  have trail S ⊨as CNot D using conf confl by auto
  then have vars-of-D: atms-of D ⊆ atm-of ' lits-of-l (trail S)
    unfolding atms-of-def
    by (meson image-subsetI true-annots-CNot-all-atms-defined)
  have vars-of-D: atms-of ?D' ⊆ atm-of ' lits-of-l M1
    using backtrack-atms-of-D-in-M1[of S D L i K M1 M2 T] T backtrack lev confl
    by (auto simp: cdclW-M-level-inv-decomp)
  have no-dup (trail S) using lev by (auto simp: cdclW-M-level-inv-decomp)
  then have ∀ x ∈ atms-of ?D'. x ∉ atm-of ' lits-of-l (M0 @ M2 @ Decided K # [])
    using vars-of-D distinct-atms-of-incl-not-in-other[of
      M0 @ M2 @ Decided K # [] M1] unfolding M by auto
  then have M1 ⊨as CNot ?D'
    using true-annots-remove-if-notin-vars[of M0 @ M2 @ Decided K # []
      M1 CNot ?D'] ⟨trail S ⊨as CNot D⟩ unfolding M lits-of-def
    by (simp add: true-annot-CNot-diff)
  then show b ⊨as CNot (mark - {#La#}) ∧ La ∈# mark
    using P LD b by auto
next
  case tl-tr
  then obtain c' where c' @ Propagated La mark # b = trail S
    unfolding M by auto
  then show b ⊨as CNot (mark - {#La#}) ∧ La ∈# mark
    using mark-confl by auto
qed
qed
qed

```

lemma *cdcl_W-conflicting-is-false:*

```

assumes
  cdclW S S' and
  M-lev: cdclW-M-level-inv S and
  confl-inv: ∀ T. conflicting S = Some T ⟶ trail S ⊨as CNot T and
  decided-confl: ∀ L mark a b. a @ Propagated L mark # b = (trail S)
    ⟶ (b ⊨as CNot (mark - {#L#}) ∧ L ∈# mark) and
  dist: distinct-cdclW-state S
shows ∀ T. conflicting S' = Some T ⟶ trail S' ⊨as CNot T
using assms(1,2)
proof (induct rule: cdclW-all-induct)

```

```

  case (skip L C' M D T) note tr-S = this(1) and confl = this(2) and L-D = this(3) and T =
this(5)
  have D: Propagated L C' # M  $\models_{as}$  CNot D using assms skip by auto
  moreover
  have L  $\notin$  # D
  proof (rule ccontr)
    assume  $\neg$  ?thesis
    then have  $- L \in \text{ lits-of-l } M$ 
      using in-CNot-implies-uminus(2)[of L D Propagated L C' # M]
       $\langle$  Propagated L C' # M  $\models_{as}$  CNot D  $\rangle$  by simp
    then show False
      by (metis (no-types, hide-lams) M-lev cdclW-M-level-inv-decomp(1) consistent-interp-def
          image-insert insert-iff list.set(2) lits-of-def ann-lit.sel(2) tr-S)
  qed
  ultimately show ?case
    using tr-S confl L-D T unfolding cdclW-M-level-inv-def
    by (auto intro: true-annots-CNot-lit-of-notin-skip)
next
  case (resolve L C M D T) note tr = this(1) and LC = this(2) and confl = this(4) and LD =
this(5)
  and T = this(7)
  let ?C = remove1-mset L C
  let ?D = remove1-mset ( $-L$ ) D
  show ?case
  proof (intro allI impI)
    fix T'
    have tl (trail S)  $\models_{as}$  CNot ?C using tr decided-confl by fastforce
    moreover
    have distinct-mset (?D + {# $-L$ #}) using confl dist LD
      unfolding distinct-cdclW-state-def by auto
    then have  $-L \notin$  # ?D unfolding distinct-mset-def
      by (meson  $\langle$  distinct-mset (?D + {# $-L$ #})  $\rangle$  distinct-mset-single-add)
    have M  $\models_{as}$  CNot ?D
    proof  $-$ 
      have Propagated L (?C + {#L#}) # M  $\models_{as}$  CNot ?D  $\cup$  CNot {# $-L$ #}
        using confl tr confl-inv LC by (metis CNot-plus LD insert-DiffM2)
      then show ?thesis
        using M-lev  $\langle -L \notin$  # ?D  $\rangle$  tr true-annots-lit-of-notin-skip
        unfolding cdclW-M-level-inv-def by force
    qed
    moreover assume conflicting T = Some T'
    ultimately
    show trail T  $\models_{as}$  CNot T'
      using tr T by auto
  qed
qed (auto simp: M-lev cdclW-M-level-inv-decomp)

lemma cdclW-conflicting-decomp:
  assumes cdclW-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 cdclW-conflicting-def by blast+

lemma cdclW-conflicting-decomp2:
  assumes cdclW-conflicting S and conflicting S = Some T

```

shows *trail S* \models_{as} *CNot T*
using *assms* **unfolding** *cdcl_W-conflicting-def* **by** *blast+*

lemma *cdcl_W-conflicting-S0-cdcl_W[simp]*:
cdcl_W-conflicting (*init-state N*)
unfolding *cdcl_W-conflicting-def* **by** *auto*

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-ann-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-ann-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-ann-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 *rtrancp-cdcl_W-all-inv*:

assumes

cdcl_W: *rtrancp cdcl_W S S'* **and**

1: *all-decomposition-implies-m* (*init-clss S*) (*get-all-ann-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-ann-decomposition* (*trail S'*)) **and**

cdcl_W-learned-clause S' **and**

cdcl_W-M-level-inv S' **and**

no-strange-atm S' **and**

distinct-cdcl_W-state S' **and**

cdcl_W-conflicting S'

using *assms*

```

proof (induct rule: rtrancpl-induct)
  case base
    case 1 then show ?case by blast
    case 2 then show ?case by blast
    case 3 then show ?case by blast
    case 4 then show ?case by blast
    case 5 then show ?case by blast
    case 6 then show ?case by blast
  next
    case (step S' S'') note H = this
      case 1 with H(3-7)[OF this(1-6)] show ?case using cdclW-all-inv[OF H(2)]
        H by presburger
      case 2 with H(3-7)[OF this(1-6)] show ?case using cdclW-all-inv[OF H(2)]
        H by presburger
      case 3 with H(3-7)[OF this(1-6)] show ?case using cdclW-all-inv[OF H(2)]
        H by presburger
      case 4 with H(3-7)[OF this(1-6)] show ?case using cdclW-all-inv[OF H(2)]
        H by presburger
      case 5 with H(3-7)[OF this(1-6)] show ?case using cdclW-all-inv[OF H(2)]
        H by presburger
      case 6 with H(3-7)[OF this(1-6)] show ?case using cdclW-all-inv[OF H(2)]
        H by presburger
  qed

lemma all-invariant-S0-cdclW:
  assumes distinct-mset-mset N
  shows
    all-decomposition-implies-m (init-clss (init-state N))
      (get-all-ann-decomposition (trail (init-state N))) and
    cdclW-learned-clause (init-state N) and
     $\forall T. \text{conflicting } (init-state N) = \text{Some } T \longrightarrow (\text{trail } (init-state N)) \models_{as} CNot T$  and
    no-strange-atm (init-state N) and
    consistent-interp (lits-of-l (trail (init-state N))) and
     $\forall L \text{ mark } a \ b. a @ \text{Propagated } L \text{ mark } \# \ b = \text{trail } (init-state N) \longrightarrow$ 
      ( $b \models_{as} CNot (\text{mark} - \{\#L\}) \wedge L \in \# \text{ mark}$ ) and
    distinct-cdclW-state (init-state N)
  using assms by auto

```

Item 6 page 81 of Weidenbach's book

```

lemma cdclW-only-propagated-vars-unsat:
  assumes
    decided:  $\forall x \in \text{set } M. \neg \text{is-decided } x$  and
    DN:  $D \in \# \text{ clauses } S$  and
    D:  $M \models_{as} CNot D$  and
    inv: all-decomposition-implies-m N (get-all-ann-decomposition M) and
    state: state S = (M, N, U, k, C) and
    learned-cl: cdclW-learned-clause S and
    atm-incl: no-strange-atm S
  shows unsatisfiable (set-mset N)
proof (rule ccontr)
  assume  $\neg \text{unsatisfiable } (set-mset N)$ 
  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-mm  $N \cup \text{atms-of-mm } U = \text{atms-of-mm } N$ 
  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 then have total-over-m  $I$  (set-mset (learned-clss  $S$ ))
  using atm-incl state unfolding no-strange-atm-def total-over-m-def total-over-set-def
  by auto
moreover have  $N \models_{psm} U$  using learned-cl state unfolding cdclW-learned-clause-def by auto
ultimately have  $I-D: I \models D$ 
  using  $I \text{ DN cons state unfolding true-clss-clss-def true-clss-def Ball-def}$ 
  by (auto simp add: clauses-def)

have  $l0: \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } M\} = \{\}$  using decided by auto
have atms-of-ms (set-mset  $N \cup \text{unmark-l } M$ ) = atms-of-mm  $N$ 
  using atm-incl state unfolding no-strange-atm-def by auto
then have total-over-m  $I$  (set-mset  $N \cup \text{unmark-l } M$ )
  using tot unfolding total-over-m-def by auto
then have  $I \models_s \text{unmark-l } M$ 
  using all-decomposition-implies-propagated-lits-are-implied[OF inv] cons  $I$ 
  unfolding true-clss-clss-def  $l0$  by auto
then have  $IM: I \models_s \text{unmark-l } M$  by auto
{
  fix  $K$ 
  assume  $K \in \# D$ 
  then have  $-K \in \text{lits-of-l } M$ 
    using  $D$  unfolding true-annots-def Ball-def CNot-def true-annot-def true-clss-def true-lit-def
    Bex-def by force
  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-clss-def true-lit-def consistent-interp-def by auto
then show False using  $I-D$  by blast
}
qed

```

Item 5 page 81 of Weidenbach's book

We have actually a much stronger theorem, namely *all-decomposition-implies-propagated-lits-are-implied*, that show that the only choices we made are decided in the formula

lemma

```

assumes all-decomposition-implies-m  $N$  (get-all-ann-decomposition  $M$ )
and  $\forall m \in \text{set } M. \neg \text{is-decided } m$ 
shows set-mset  $N \models_{ps} \text{unmark-l } M$ 

```

proof –

```

have  $T: \{\text{unmark } L \mid L. \text{is-decided } L \wedge L \in \text{set } M\} = \{\}$  using assms(2) by auto
then show ?thesis
  using all-decomposition-implies-propagated-lits-are-implied[OF assms(1)] unfolding  $T$  by simp

```

qed

Item 7 page 81 of Weidenbach's book (part 1)

lemma *conflict-with-false-implies-unsat*:

```

assumes
  cdclW: cdclW  $S S'$  and
  lev: cdclW-M-level-inv  $S$  and
  [simp]: conflicting  $S' = \text{Some } \{\#\}$  and
  learned: cdclW-learned-clause  $S$ 
shows unsatisfiable (set-mset (init-clss  $S$ ))

```

using assms

proof –


```

have cdclW-learned-clause S' using cdclW-learned-clss cdclW learned lev by auto
then have init-clss S'  $\models_{pm} \{\#\}$  using assms(3) unfolding cdclW-learned-clause-def by auto
then have init-clss S  $\models_{pm} \{\#\}$ 
  using cdclW-init-clss[OF assms(1) lev] by auto
then show ?thesis unfolding satisfiable-def true-clss-clss-def by auto
qed

```

Item 7 page 81 of Weidenbach's book (part 2)

```

lemma conflict-with-false-implies-terminated:
  assumes cdclW S S'
  and conflicting S = Some {#}
  shows False
  using assms by (induct rule: cdclW-all-induct) auto

```

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
    cdclW S S' and
    lev: cdclW-M-level-inv S and
    conflicting: cdclW-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: cdclW-all-induct)
  case (backtrack L D K i M1 M2 T) note confl = this(1)
  have consistent-interp (lits-of-l (trail S)) using lev by (auto simp: cdclW-M-level-inv-decomp)
  moreover
    have trail S  $\models_{as} \text{CNot } D$ 
    using conflicting confl unfolding cdclW-conflicting-def by auto
  then have lits-of-l (trail S)  $\models_s \text{CNot } D$ 
    using true-annots-true-clss by blast
  ultimately have  $\neg \text{tautology } D$  using consistent-CNot-not-tautology by blast
  then show ?case using backtrack no-tauto lev
    by (auto simp: cdclW-M-level-inv-decomp split: if-split-asm)
next
  case restart
  then show ?case using state-eq-learned-clss no-tauto
    by (auto intro: atms-of-ms-learned-clss-restart-state-in-atms-of-ms-learned-clssI)
qed (auto dest!: in-diffD)

```

```

definition final-cdclW-state (S :: 'st)
   $\longleftrightarrow$  (trail S  $\models_{asm} \text{init-clss } S$ 
     $\vee ((\forall L \in \text{set } (\text{trail } S). \neg \text{is-decided } L) \wedge$ 
       $(\exists C \in \# \text{ init-clss } S. \text{trail } S \models_{as} \text{CNot } C)))$ 

```

```

definition termination-cdclW-state (S :: 'st)
   $\longleftrightarrow$  (trail S  $\models_{asm} \text{init-clss } S$ 
     $\vee ((\forall L \in \text{atms-of-mm } (\text{init-clss } S). L \in \text{atm-of ' lits-of-l } (\text{trail } S))$ 
       $\wedge (\exists C \in \# \text{ init-clss } S. \text{trail } S \models_{as} \text{CNot } C)))$ 

```

6.1.4 CDCL Strong Completeness

lemma *cdcl_W-can-do-step*:

```

assumes
  consistent-interp (set M) and
  distinct M and
  atm-of ' (set M)  $\subseteq$  atms-of-mm N
shows  $\exists S. \text{rtrancpl } \text{cdcl}_W \text{ (init-state } N) S$ 
   $\wedge \text{state } S = (\text{map } (\lambda L. \text{Decided } L) M, N, \{\#\}, \text{length } M, \text{None})$ 
using assms
proof (induct M)
  case Nil
  then show ?case apply – by (rule exI[of - init-state N]) 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-mm N
    using Cons.prems(1–3) unfolding consistent-interp-def by auto
  then obtain S where
    st: cdclW** (init-state N) S and
    S: state S = (map ( $\lambda L. \text{Decided } L$ ) M, N, {#}, length M, None)
    using IH by blast
  let ?S0 = incr-lvl (cons-trail (Decided L) S)
  have undefined-lit (map ( $\lambda L. \text{Decided } L$ ) M) L
    using Cons.prems(1,2) unfolding defined-lit-def consistent-interp-def by fastforce
  moreover have init-clss S = N
    using S by blast
  moreover have atm-of L  $\in$  atms-of-mm N using Cons.prems(3) by auto
  moreover have undef: undefined-lit (trail S) L
    using S  $\langle \text{distinct } (L \# M) \rangle$  calculation(1) by (auto simp: defined-lit-map)
  ultimately have cdclW S ?S0
    using cdclW.other[OF cdclW.o.decide[OF decide-rule[of S L ?S0]]] S
    by (auto simp: state-eq-def simp del: state-simp)
  then have cdclW** (init-state N) ?S0
    using st by auto
  then show ?case
    using S undef by (auto intro!: exI[of - ?S0] del: simp del: )
qed

```

theorem 2.9.11 page 84 of Weidenbach's book

lemma *cdcl_W-strong-completeness*:

```

assumes
  MN: set M  $\models_{sm}$  N and
  cons: consistent-interp (set M) and
  dist: distinct M and
  atm: atm-of ' (set M)  $\subseteq$  atms-of-mm N
obtains S where
  state S = (map ( $\lambda L. \text{Decided } L$ ) M, N, {#}, length M, None) and
  rtrancpl cdclW (init-state N) S and
  final-cdclW-state S
proof –
  obtain S where
    st: rtrancpl cdclW (init-state N) S and
    S: state S = (map ( $\lambda L. \text{Decided } L$ ) M, N, {#}, length M, None)
    using cdclW-can-do-step[OF cons dist atm] by auto
  have lits-of-l (map ( $\lambda L. \text{Decided } L$ ) M) = set M
    by (induct M, auto)

```

```

then have map ( $\lambda L. \text{Decided } L$ )  $M \models_{asm} N$  using  $MN \text{ true-annots-true-cls}$  by metis
then have  $\text{final-cdcl}_W\text{-state } S$ 
  using  $S$  unfolding  $\text{final-cdcl}_W\text{-state-def}$  by auto
then show ?thesis using that st  $S$  by blast
qed

```

6.1.5 Higher level strategy

The rules described previously do not lead to a conclusive state. We have to add a strategy.

Definition

```

lemma trancpl-conflict:
   $\text{trancpl conflict } S S' \implies \text{conflict } S S'$ 
  apply (induct rule: trancpl.induct)
  apply simp
  by (metis conflictE conflicting-update-conflicting option.distinct(1) state-eq-conflicting)

```

```

lemma trancpl-conflict-iff[iff]:
   $\text{full1 conflict } S S' \longleftrightarrow \text{conflict } S S'$ 
proof -
  have  $\text{trancpl conflict } S S' \implies \text{conflict } S S'$  by (meson trancpl-conflict rtrancplD)
  then show ?thesis unfolding full1-def
  by (metis conflict.simps conflicting-update-conflicting option.distinct(1) state-eq-conflicting trancpl.intros(1))
qed

```

```

inductive  $\text{cdcl}_W\text{-cp} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$  where
  conflict'[intro]:  $\text{conflict } S S' \implies \text{cdcl}_W\text{-cp } S S' \mid$ 
  propagate':  $\text{propagate } S S' \implies \text{cdcl}_W\text{-cp } S S'$ 

```

```

lemma rtrancpl-cdclW-cp-rtrancpl-cdclW:
   $\text{cdcl}_W\text{-cp}^{**} S T \implies \text{cdcl}_W^{**} S T$ 
  by (induction rule: rtrancpl-induct) (auto simp: cdclW-cp.simps dest: cdclW.intros)

```

```

lemma cdclW-cp-state-eq-compatible:
  assumes
     $\text{cdcl}_W\text{-cp } S T$  and
     $S \sim S'$  and
     $T \sim T'$ 
  shows  $\text{cdcl}_W\text{-cp } S' T'$ 
  using assms
  apply (induction)
  using conflict-state-eq-compatible apply auto[1]
  using propagate' propagate-state-eq-compatible by auto

```

```

lemma trancpl-cdclW-cp-state-eq-compatible:
  assumes
     $\text{cdcl}_W\text{-cp}^{++} S T$  and
     $S \sim S'$  and
     $T \sim T'$ 
  shows  $\text{cdcl}_W\text{-cp}^{++} S' T'$ 
  using assms
proof induction
  case base

```

```

then show ?case
  using cdclW-cp-state-eq-compatible by blast
next
case (step U V)
obtain ss :: 'st where
  cdclW-cp S ss and cdclW-cp** ss U
by (metis (no-types) step(1) tranclpD)
then show ?case
  by (meson cdclW-cp-state-eq-compatible rtranclp.rtrancl-into-rtrancl rtranclp-into-tranclp2
      state-eq-ref step(2) step(4) step(5))
qed

lemma option-full-cdclW-cp:
  conflicting S ≠ None ⇒ full cdclW-cp S S
  unfolding full-def rtranclp-unfold tranclp-unfold
  by (auto simp add: cdclW-cp.simps elim: conflictE propagateE)

lemma skip-unique:
  skip S T ⇒ skip S T' ⇒ T ∼ T'
  by (fastforce simp: state-eq-def simp del: state-simp elim: skipE)

lemma resolve-unique:
  resolve S T ⇒ resolve S T' ⇒ T ∼ T'
  by (fastforce simp: state-eq-def simp del: state-simp elim: resolveE)

lemma cdclW-cp-no-more-clauses:
  assumes cdclW-cp S S'
  shows clauses S = clauses S'
  using assms by (induct rule: cdclW-cp.induct) (auto elim!: conflictE propagateE)

lemma tranclp-cdclW-cp-no-more-clauses:
  assumes cdclW-cp++ S S'
  shows clauses S = clauses S'
  using assms by (induct rule: tranclp.induct) (auto dest: cdclW-cp-no-more-clauses)

lemma rtranclp-cdclW-cp-no-more-clauses:
  assumes cdclW-cp** S S'
  shows clauses S = clauses S'
  using assms by (induct rule: rtranclp.induct) (fastforce dest: cdclW-cp-no-more-clauses)+

lemma no-conflict-after-conflict:
  conflict S T ⇒ ¬conflict T U
  by (metis conflictE conflicting-update-conflicting option.distinct(1) state-simp(5))

lemma no-propagate-after-conflict:
  conflict S T ⇒ ¬propagate T U
  by (metis conflictE conflicting-update-conflicting option.distinct(1) propagate.cases
      state-eq-conflicting)

lemma tranclp-cdclW-cp-propagate-with-conflict-or-not:
  assumes cdclW-cp++ S U
  shows (propagate++ S U ∧ conflicting U = None)
    ∨ (∃ T D. propagate** S T ∧ conflict T U ∧ conflicting U = Some D)
proof -
  have propagate++ S U ∨ (∃ T. propagate** S T ∧ conflict T U)
  using assms by induction

```

(force simp: cdcl_W-cp.simps tranclp-into-rtranclp dest: no-conflict-after-conflict
 no-propagate-after-conflict)+
moreover
 have propagate⁺⁺ S U \implies conflicting U = None
 unfolding tranclp-unfold-end by (auto elim!: propagateE)
moreover
 have $\bigwedge T. \text{conflict } T \ U \implies \exists D. \text{conflicting } U = \text{Some } D$
 by (auto elim!: conflictE simp: state-eq-def simp del: state-simp)
ultimately show ?thesis by meson
qed

lemma cdcl_W-cp-conflicting-not-empty[simp]: conflicting S = Some D $\implies \neg$ cdcl_W-cp S S'
proof
 assume cdcl_W-cp S S' and conflicting S = Some D
 then show False by (induct rule: cdcl_W-cp.induct)
 (auto elim: conflictE propagateE simp: state-eq-def simp del: state-simp)
qed

lemma no-step-cdcl_W-cp-no-conflict-no-propagate:
 assumes no-step cdcl_W-cp S
 shows no-step conflict S and no-step propagate S
 using assms conflict' apply blast
 by (meson assms conflict' propagate')

CDCL with the reasonable strategy: we fully propagate the conflict and propagate, then we
 apply any other possible rule cdcl_W-o S S' and re-apply conflict and propagate cdcl_W-cp[↓] S'
 S''

inductive cdcl_W-stgy :: 'st \Rightarrow 'st \Rightarrow bool for S :: 'st where
 conflict': full1 cdcl_W-cp S S' \implies cdcl_W-stgy S S' |
 other': cdcl_W-o S S' \implies no-step cdcl_W-cp S \implies full cdcl_W-cp S' S'' \implies cdcl_W-stgy S S''

Invariants

These are the same invariants as before, but lifted

lemma cdcl_W-cp-learned-clause-inv:
 assumes cdcl_W-cp S S'
 shows learned-clss S = learned-clss S'
 using assms by (induct rule: cdcl_W-cp.induct) (fastforce elim: conflictE propagateE)+

lemma rtranclp-cdcl_W-cp-learned-clause-inv:
 assumes cdcl_W-cp^{**} S S'
 shows learned-clss S = learned-clss S'
 using assms by (induct rule: rtranclp-induct) (fastforce dest: cdcl_W-cp-learned-clause-inv)+

lemma tranclp-cdcl_W-cp-learned-clause-inv:
 assumes cdcl_W-cp⁺⁺ S S'
 shows learned-clss S = learned-clss S'
 using assms by (simp add: rtranclp-cdcl_W-cp-learned-clause-inv tranclp-into-rtranclp)

lemma cdcl_W-cp-backtrack-lvl:
 assumes cdcl_W-cp S S'
 shows backtrack-lvl S = backtrack-lvl S'
 using assms by (induct rule: cdcl_W-cp.induct) (fastforce elim: conflictE propagateE)+

lemma rtranclp-cdcl_W-cp-backtrack-lvl:

assumes $cdcl_W\text{-cp}^{**} S S'$
shows $backtrack\text{-lvl } S = backtrack\text{-lvl } S'$
using *assms* **by** (*induct rule: rtranclp-induct*) (*fastforce dest: cdcl_W-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-cp.induct*)
case (*conflict'*)
then show ?*case* **using** $cdcl_W\text{-consistent-inv } cdcl_W.conflict$ **by** *blast*
next
case (*propagate' S S'*)
have $cdcl_W S S'$
using $propagate'.hyps(1)$ *propagate* **by** *blast*
then show $cdcl_W\text{-M-level-inv } S'$
using $propagate'.prems(1)$ $cdcl_W\text{-consistent-inv } propagate$ **by** *blast*
qed

lemma $full1\text{-}cdcl_W\text{-cp-consistent-inv}$:
assumes $full1\ cdcl_W\text{-cp } S S'$ **and** $cdcl_W\text{-M-level-inv } S$
shows $cdcl_W\text{-M-level-inv } S'$
using *assms* **unfolding** $full1\text{-def}$
by (*metis rtranclp-cdcl_W-cp-rtranclp-cdcl_W rtranclp-unfold tranclp-cdcl_W-consistent-inv*)

lemma $rtranclp\text{-}cdcl_W\text{-cp-consistent-inv}$:
assumes $rtranclp\ cdcl_W\text{-cp } S S'$ **and** $cdcl_W\text{-M-level-inv } S$
shows $cdcl_W\text{-M-level-inv } S'$
using *assms* **unfolding** $full1\text{-def}$
by (*induction rule: rtranclp-induct*) (*blast intro: cdcl_W-cp-consistent-inv*)+

lemma $cdcl_W\text{-stgy-consistent-inv}$:
assumes $cdcl_W\text{-stgy } S S'$ **and** $cdcl_W\text{-M-level-inv } S$
shows $cdcl_W\text{-M-level-inv } S'$
using *assms* **apply** (*induct rule: cdcl_W-stgy.induct*)
unfolding $full\text{-unfold}$ **by** (*blast intro: cdcl_W-consistent-inv full1-cdcl_W-cp-consistent-inv cdcl_W.other*)+

lemma $rtranclp\text{-}cdcl_W\text{-stgy-consistent-inv}$:
assumes $cdcl_W\text{-stgy}^{**} S S'$ **and** $cdcl_W\text{-M-level-inv } S$
shows $cdcl_W\text{-M-level-inv } S'$
using *assms* **by** *induction* (*auto dest!: cdcl_W-stgy-consistent-inv*)

lemma $cdcl_W\text{-cp-no-more-init-clss}$:
assumes $cdcl_W\text{-cp } S S'$
shows $init\text{-clss } S = init\text{-clss } S'$
using *assms* **by** (*induct rule: cdcl_W-cp.induct*) (*auto elim: conflictE propagateE*)

lemma $tranclp\text{-}cdcl_W\text{-cp-no-more-init-clss}$:
assumes $cdcl_W\text{-cp}^{++} S S'$
shows $init\text{-clss } S = init\text{-clss } S'$
using *assms* **by** (*induct rule: tranclp.induct*) (*auto dest: cdcl_W-cp-no-more-init-clss*)

lemma $cdcl_W\text{-stgy-no-more-init-clss}$:
assumes $cdcl_W\text{-stgy } S S'$ **and** $cdcl_W\text{-M-level-inv } S$
shows $init\text{-clss } S = init\text{-clss } S'$

using *assms*
apply (*induct rule: cdcl_W-stgy.induct*)
unfolding *full1-def full-def* **apply** (*blast dest: tranclp-cdcl_W-cp-no-more-init-clss*
tranclp-cdcl_W-o-no-more-init-clss)
by (*metis cdcl_W-o-no-more-init-clss rtranclp-unfold tranclp-cdcl_W-cp-no-more-init-clss*)

lemma *rtranclp-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: rtranclp-induct, simp*)
using *cdcl_W-stgy-no-more-init-clss* **by** (*simp add: rtranclp-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** $(\forall l \in \text{set } M. \neg \text{is-decided } l)$
using *assms* **by** *induction (fastforce elim: conflictE propagateE)+*

lemma *rtranclp-cdcl_W-cp-dropWhile-trail'*:
assumes *cdcl_W-cp** S S'*
obtains *M :: ('v, 'v clause) ann-lits* **where**
trail S' = M @ trail S **and** $\forall l \in \text{set } M. \neg \text{is-decided } l$
using *assms* **by** *induction (fastforce dest!: cdcl_W-cp-dropWhile-trail')+*

lemma *cdcl_W-cp-dropWhile-trail*:
assumes *cdcl_W-cp S S'*
shows $\exists M. \text{trail } S' = M @ \text{trail } S \wedge (\forall l \in \text{set } M. \neg \text{is-decided } l)$
using *assms* **by** *induction (fastforce elim: conflictE propagateE)+*

lemma *rtranclp-cdcl_W-cp-dropWhile-trail*:
assumes *cdcl_W-cp** S S'*
shows $\exists M. \text{trail } S' = M @ \text{trail } S \wedge (\forall l \in \text{set } M. \neg \text{is-decided } l)$
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-mm (init-clss S))
shows $\text{length } (\text{trail } S) \leq \text{card } (\text{atms-of-mm } (\text{init-clss } S))$

proof –

obtain *M N U k D* **where** *S: state S = (M, N, U, k, D)* **by** (*cases state S, auto*)
have *finite (atm-of ' lits-of-l (trail S))*
using *assms(1,3) unfolding S* **by** (*auto simp add: finite-subset*)
have $\text{length } (\text{trail } S) = \text{card } (\text{atm-of ' lits-of-l } (\text{trail } S))$
using *no-dup-length-eq-card-atm-of-lits-of-l no-d* **by** *blast*
then show *?thesis* **using** *assms(1) unfolding no-strange-atm-def*
by (*auto simp add: assms(3) card-mono*)

qed

lemma *cdcl_W-cp-decreasing-measure*:
assumes
cdcl_W: cdcl_W-cp S T **and**
M-lev: cdcl_W-M-level-inv S **and**
alien: no-strange-atm S

```

shows ( $\lambda S. \text{card} (\text{atms-of-mm} (\text{init-clss } S)) - \text{length} (\text{trail } S)$ 
  + (if conflicting  $S = \text{None}$  then 1 else 0))  $S$ 
  > ( $\lambda S. \text{card} (\text{atms-of-mm} (\text{init-clss } S)) - \text{length} (\text{trail } S)$ 
  + (if conflicting  $S = \text{None}$  then 1 else 0))  $T$ 
using assms
proof -
  have  $\text{length} (\text{trail } T) \leq \text{card} (\text{atms-of-mm} (\text{init-clss } T))$ 
  apply (rule length-model-le-vars)
    using cdclW-no-strange-atm-inv alien M-lev apply (meson cdclW cdclW.simps cdclW-cp.cases)
    using M-lev cdclW cdclW-cp-consistent-inv cdclW-M-level-inv-def apply blast
    using cdclW by (auto simp: cdclW-cp.simps)
  with assms
  show ?thesis by induction (auto elim!: conflictE propagateE
    simp del: state-simp simp: state-eq-def)+
qed

lemma cdclW-cp-wf:  $\text{wf} \{(b, a). (\text{cdcl}_W\text{-M-level-inv } a \wedge \text{no-strange-atm } a) \wedge \text{cdcl}_W\text{-cp } a \ b\}$ 
apply (rule wf-wf-if-measure'[of less-than - -
  ( $\lambda S. \text{card} (\text{atms-of-mm} (\text{init-clss } S)) - \text{length} (\text{trail } S)$ 
  + (if conflicting  $S = \text{None}$  then 1 else 0))]))
apply simp
using cdclW-cp-decreasing-measure unfolding less-than-iff by blast

lemma rtranclp-cdclW-all-struct-inv-cdclW-cp-iff-rtranclp-cdclW-cp:
assumes
  lev: cdclW-M-level-inv S and
  alien: no-strange-atm S
shows ( $\lambda a \ b. (\text{cdcl}_W\text{-M-level-inv } a \wedge \text{no-strange-atm } a) \wedge \text{cdcl}_W\text{-cp } a \ b)^{**} S \ T$ 
 $\longleftrightarrow \text{cdcl}_W\text{-cp}^{**} S \ T$ 
(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  $\text{cdcl}_W^{**} S \ T$ 
      by (metis rtranclp-unfold cdclW-cp-conflicting-not-empty cp st
        rtranclp-propagate-is-rtranclp-cdclW tranclp-cdclW-cp-propagate-with-conflict-or-not)
    then have
      cdclW-M-level-inv T and
      no-strange-atm T
      using  $\langle \text{cdcl}_W^{**} S \ T \rangle$  apply (simp add: assms(1) rtranclp-cdclW-consistent-inv)
      using  $\langle \text{cdcl}_W^{**} S \ T \rangle$  alien rtranclp-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 *cdcl_W-cp-normalized-element*:

assumes

lev: *cdcl_W-M-level-inv S* **and**

no-strange-atm S

obtains *T* **where** *full cdcl_W-cp S T*

proof –

let *?inv* = $\lambda a. (cdcl_W\text{-}M\text{-level-inv } a \wedge no\text{-strange-atm } a)$

obtain *T* **where** *T*: *full* ($\lambda a b. ?inv a \wedge cdcl_W\text{-}cp a b$) *S T*

using *cdcl_W-cp-wf wf-exists-normal-form*[*of* $\lambda a b. ?inv a \wedge cdcl_W\text{-}cp a b$]

unfolding *full-def* **by** *blast*

then have *cdcl_W-cp** S T*

using *rtrancpl-cdcl_W-all-struct-inv-cdcl_W-cp-iff-rtrancpl-cdcl_W-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 *always-exists-full-cdcl_W-cp-step*:

assumes *no-strange-atm S*

shows $\exists S''. full\ cdcl_W\text{-}cp\ S\ S''$

using *assms*

proof (*induct card (atms-of-mm (init-clss S) – atm-of ‘lits-of-l (trail S)) arbitrary: S*)

case *0* **note** *card = this(1)* **and** *alien = this(2)*

then have *atm: atms-of-mm (init-clss S) = atm-of ‘lits-of-l (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 $\forall S''. \neg cdcl_W\text{-}cp\ S'\ S''$

by (*auto simp: cdcl_W-cp.simps elim!: conflictE propagateE*

simp del: state-simp simp: state-eq-def)

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 *E L* **where**

S: *conflicting S = None* **and**

E: *E* $\in \#$ *clauses S* **and**

LE: *L* $\in \#$ *E* **and**

tr: *trail S* $\models_{as} CNot (E - \{\#L\# \})$ **and**

undef: *undefined-lit (trail S) L* **and**

S': *S' ~ cons-trail (Propagated L E) S*

by (*elim propagateE*) *simp*

have *atms-of-mm (learned-clss S) \subseteq atms-of-mm (init-clss S)*

using *alien S* **unfolding** *no-strange-atm-def* **by** *auto*

then have *atm-of L \in atms-of-mm (init-clss S)*

```

    using E LE S undef unfolding clauses-def by (force simp: in-implies-atm-of-on-atms-of-ms)
  then have False using undef S unfolding atm unfolding lits-of-def
    by (auto simp add: defined-lit-map)
}
ultimately show ?case unfolding full-def by (metis cdclW-cp.cases rtranclp.rtrancl-refl)
next
case (Suc n) note IH = this(1) and card = this(2) and alien = this(3)
{ assume a:  $\exists S'. \text{conflict } S S'$ 
  then obtain S' where S':  $\text{conflict } S S'$  by metis
  then have  $\forall S''. \neg \text{cdcl}_W\text{-cp } S' S''$ 
    by (auto simp: cdclW-cp.simps elim!: conflictE propagateE
      simp del: state-simp simp: state-eq-def)
  then have ?case unfolding full-def Ex-def using S' cdclW-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 E L where
    S:  $\text{conflicting } S = \text{None}$  and
    E:  $E \in \# \text{ clauses } S$  and
    LE:  $L \in \# E$  and
    tr:  $\text{trail } S \models_{\text{as}} \text{CNot } (E - \{\#L\# \})$  and
    undef:  $\text{undefined-lit } (\text{trail } S) L$  and
    S':  $S' \sim \text{cons-trail } (\text{Propagated } L E) S$ 
    by (elim propagateE) simp
  then have  $\text{atm-of } L \notin \text{atm-of 'lits-of-l } (\text{trail } S)$ 
    unfolding lits-of-def by (auto simp add: defined-lit-map)
  moreover
    have no-strange-atm S' using alien propagate propagate-no-strange-atm-inv by blast
    then have  $\text{atm-of } L \in \text{atms-of-mm } (\text{init-clss } S)$ 
      using S' LE E undef unfolding no-strange-atm-def
      by (auto simp: clauses-def in-implies-atm-of-on-atms-of-ms)
    then have  $\bigwedge A. \{\text{atm-of } L\} \subseteq \text{atms-of-mm } (\text{init-clss } S) - A \vee \text{atm-of } L \in A$  by force
  moreover have  $\text{Suc } n - \text{card } \{\text{atm-of } L\} = n$  by simp
  moreover have  $\text{card } (\text{atms-of-mm } (\text{init-clss } S) - \text{atm-of 'lits-of-l } (\text{trail } S)) = \text{Suc } n$ 
    using card S S' by simp
  ultimately
    have  $\text{card } (\text{atms-of-mm } (\text{init-clss } S) - \text{atm-of 'insert } L (\text{lits-of-l } (\text{trail } S))) = n$ 
      by (metis (no-types) Diff-insert card-Diff-subset finite.emptyI finite.insertI image-insert)
    then have  $n = \text{card } (\text{atms-of-mm } (\text{init-clss } S') - \text{atm-of 'lits-of-l } (\text{trail } S'))$ 
      using card S S' undef by simp
  then have a1:  $\text{Ex } (\text{full cdcl}_W\text{-cp } S')$  using IH <no-strange-atm S'> by blast
  have ?case
    proof -
      obtain S'' :: 'st where
        ff1:  $\text{cdcl}_W\text{-cp}^{**} S' S'' \wedge \text{no-step cdcl}_W\text{-cp } S''$ 
        using a1 unfolding full-def by blast
      have  $\text{cdcl}_W\text{-cp}^{**} S S''$ 
        using ff1 cdclW-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 cdcl_W-cp.cases rtranclp.rtrancl-refl)
qed

Literal of highest level in conflicting clauses

One important property of the *cdcl_W* with strategy is that, whenever a conflict takes place, there is at least a literal of level *k* involved (except if we have derived the false clause). The reason is that we apply conflicts before a decision is taken.

abbreviation *no-clause-is-false* :: 'st ⇒ bool **where**

no-clause-is-false ≡

λ*S*. (conflicting *S* = None ⟶ (∀ *D* ∈# clauses *S*. ¬trail *S* ⊨_{as} CNot *D*))

abbreviation *conflict-is-false-with-level* :: 'st ⇒ bool **where**

conflict-is-false-with-level *S* ≡ ∀ *D*. conflicting *S* = Some *D* ⟶ *D* ≠ {#}
⟶ (∃ *L* ∈# *D*. get-level (trail *S*) *L* = backtrack-lvl *S*)

lemma *not-conflict-not-any-negated-init-clss*:

assumes ∀ *S*'. ¬conflict *S* *S*'

shows *no-clause-is-false* *S*

proof (clarify)

fix *D*

assume *D* ∈# local.clauses *S* **and** conflicting *S* = None **and** trail *S* ⊨_{as} CNot *D*

then show False

using conflict-rule[of *S* *D* update-conflicting (Some *D*) *S*] assms

by auto

qed

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 auto

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 auto

lemma *cdcl_W-stgy-not-non-negated-init-clss*:

assumes cdcl_W-stgy *S* *S*'

shows *no-clause-is-false* *S*'

using assms apply (induct rule: cdcl_W-stgy.induct)

using full1-cdcl_W-cp-not-any-negated-init-clss full-cdcl_W-cp-not-any-negated-init-clss by metis+

lemma *rtranclp-cdcl_W-stgy-not-non-negated-init-clss*:

assumes cdcl_W-stgy** *S* *S*' **and** *no-clause-is-false* *S*

shows *no-clause-is-false* *S*'

using assms by (induct rule: rtranclp-induct) (auto simp: cdcl_W-stgy-not-non-negated-init-clss)

lemma *cdcl_W-stgy-conflict-ex-lit-of-max-level*:

assumes

cdcl_W-cp *S* *S*' **and**

no-clause-is-false *S* **and**

cdcl_W-*M*-level-inv *S*

shows *conflict-is-false-with-level* *S*'

using assms

```

proof (induct rule: cdclW-cp.induct)
  case conflict'
  then show ?case by (auto elim: conflictE)
next
  case propagate'
  then show ?case by (auto elim: propagateE)
qed

lemma no-chained-conflict:
  assumes conflict S S' and conflict S' S''
  shows False
  using assms unfolding conflict.simps
  by (metis conflicting-update-conflicting option.distinct(1) state-eq-conflicting)

lemma rtrancpl-cdclW-cp-propa-or-propa-conf:
  assumes cdclW-cp** S U
  shows propagate** S U  $\vee$  ( $\exists T. \text{propagate}^{**} S T \wedge \text{conflict } T U$ )
  using assms
proof induction
  case base
  then show ?case by auto
next
  case (step U V) note SU = this(1) and UV = this(2) and IH = this(3)
  consider (confl) T where propagate** S T and conflict T U
  | (propa) propagate** S U using IH by auto
  then show ?case
  proof cases
  case confl
  then have False using UV by (auto elim: conflictE)
  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 rtrancpl-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  $\exists L \in \#D. \text{get-level } (\text{trail } U) L = \text{backtrack-lvl } U$ 
  proof cases
  case SD
  then have S = U
  by (metis (no-types) assms(1) cdclW-cp-conflicting-not-empty full-def rtrancplD trancplD)
  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 full unfolding full-def
  apply (metis (no-types) rtrancpD trancp-cdclW-cp-no-more-init-clss)
  by (metis (mono-tags, lifting) full full-def rtrancp-cdclW-cp-learned-clause-inv)
obtain T where propagate** S T and TU: conflict T U
proof -
  have f5: U ≠ S
  using confl CT by force
  then have cdclW-cp++ S U
  by (metis full full-def rtrancpD)
  have  $\bigwedge p \text{ pa. } \neg \text{propagate } p \text{ pa} \vee \text{conflicting } p =$ 
    (None :: 'v clause option)
  by (auto elim: propagateE)
  then show ?thesis
  using f5 that trancp-cdclW-cp-propagate-with-conflict-or-not[OF  $\langle \text{cdcl}_W\text{-cp}^{++} \text{ S U} \rangle$ ]
  full confl CT unfolding full-def by auto
qed
obtain D' where
  conflicting T = None and
  D': D' ∈# clauses T and
  tr: trail T ⊨as CNot (D') and
  U: U ∼ update-conflicting (Some (D')) T
  using TU by (auto elim!: conflictE)
have init-clss T = init-clss S and learned-clss T = learned-clss S
  using U  $\langle \text{init-clss } U = \text{init-clss } S \rangle$   $\langle \text{learned-clss } U = \text{learned-clss } S \rangle$  by auto
then have D ∈# clauses S
  using confl U D' by (auto simp: clauses-def)
then have  $\neg \text{trail } S \models_{\text{as}} \text{CNot } D$ 
  using cls-f CT by simp

moreover
obtain M where tr-U: trail U = M @ trail S and nm:  $\forall m \in \text{set } M. \neg \text{is-decided } m$ 
  by (metis (mono-tags, lifting) assms(1) full-def rtrancp-cdclW-cp-dropWhile-trail)
have trail U ⊨as CNot D
  using tr confl U by (auto elim!: conflictE)
ultimately obtain L where L ∈# D and  $\neg L \in \text{lits-of-l } M$ 
  unfolding tr-U CNot-def true-annots-def Ball-def true-annot-def true-clss-def by force

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: rtrancp-cdclW-cp-backtrack-lvl)

moreover
  have no-dup (trail U)
  using inv-U unfolding cdclW-M-level-inv-def by auto
  { fix x :: ('v, 'v clause) ann-lit and
    xb :: ('v, 'v clause) ann-lit
    assume a1: atm-of L = atm-of (lit-of xb)
    moreover assume a2:  $\neg L = \text{lit-of } x$ 
    moreover assume a3:  $(\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ ' set } M$ 
       $\cap (\lambda l. \text{atm-of } (\text{lit-of } l)) \text{ ' set } (\text{trail } S) = \{\}$ 
    moreover assume a4:  $x \in \text{set } M$ 

```

```

moreover assume a5:  $xb \in \text{set } (\text{trail } S)$ 
moreover have atm-of  $(- L) = \text{atm-of } L$ 
  by auto
ultimately have False
  by auto
}
then have LS: atm-of  $L \notin \text{atm-of ' lits-of-l } (\text{trail } S)$ 
  using  $\langle -L \in \text{lits-of-l } M \rangle \langle \text{no-dup } (\text{trail } U) \rangle$  unfolding tr-U lits-of-def by auto
ultimately have get-level  $(\text{trail } U) L = \text{backtrack-lvl } U$ 
proof (cases count-decided  $(\text{trail } S) \neq 0$ , 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-level  $M L = 0$ 
    using nm by auto
  ultimately show ?thesis using LS ne US unfolding tr-U
    by (simp add: lits-of-def filter-empty-conv)
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 count-decided  $(\text{trail } S) = \text{backtrack-lvl } S$ 
    using ne lev unfolding cdclW-M-level-inv-def by auto
  moreover have atm-of  $L \in \text{atm-of ' lits-of-l } M$ 
    using  $\langle -L \in \text{lits-of-l } M \rangle$  by (simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
      lits-of-def)
  ultimately show ?thesis
    using nm ne get-level-skip-in-all-not-decided[of M L] unfolding lits-of-def US tr-U
    by auto
  qed
then show  $\exists L \in \#D. \text{get-level } (\text{trail } U) L = \text{backtrack-lvl } U$ 
  using  $\langle L \in \# D \rangle$  by blast
qed
qed

```

Literal of highest level in decided literals

definition mark-is-false-with-level :: 'st \Rightarrow bool **where**

mark-is-false-with-level $S' \equiv$

$\forall D M1 M2 L. M1 @ \text{Propagated } L D \# M2 = \text{trail } S' \longrightarrow D - \{\#L\} \neq \{\#\}$
 $\longrightarrow (\exists L. L \in \# D \wedge \text{get-level } (\text{trail } S') L = \text{count-decided } M1)$

definition no-more-propagation-to-do :: 'st \Rightarrow bool **where**

no-more-propagation-to-do $S \equiv$

$\forall D M M' L. D + \{\#L\} \in \# \text{ clauses } S \longrightarrow \text{trail } S = M' @ M \longrightarrow M \models_{\text{as}} \text{CNot } D$
 $\longrightarrow \text{undefined-lit } M L \longrightarrow \text{count-decided } M < \text{backtrack-lvl } S$
 $\longrightarrow (\exists L. L \in \# D \wedge \text{get-level } (\text{trail } S) L = \text{count-decided } M)$

lemma propagate-no-more-propagation-to-do:

assumes propagate: propagate $S S'$

and H: no-more-propagation-to-do S

and lev-inv: cdcl_W-M-level-inv S

shows no-more-propagation-to-do S'

using assms

proof –

obtain $E\ L$ **where**
 S : *conflicting* $S = \text{None}$ **and**
 E : $E \in \#$ *clauses* S **and**
 LE : $L \in \#$ E **and**
 tr : $\text{trail } S \models_{as} CNot\ (E - \{\#L\# \})$ **and**
 $undefL$: *undefined-lit* $(\text{trail } S)\ L$ **and**
 S' : $S' \sim \text{cons-trail}\ (\text{Propagated } L\ E)\ S$
using *propagate* **by** $(\text{elim propagate } E)\ \text{simp}$
let $?M' = \text{Propagated } L\ E\ \# \text{ trail } S$
show $?thesis$ **unfolding** *no-more-propagation-to-do-def*
proof (intro allI impI)
fix $D\ M1\ M2\ L'$
assume
 $D-L$: $D + \{\#L'\# \} \in \#$ *clauses* S' **and**
 $\text{trail } S' = M2\ @\ M1$ **and**
 get-max : *count-decided* $M1 < \text{backtrack-lvl } S'$ **and**
 $M1 \models_{as} CNot\ D$ **and**
 $undef$: *undefined-lit* $M1\ L'$
have $tl\ M2\ @\ M1 = \text{trail } S \vee (M2 = [] \wedge M1 = \text{Propagated } L\ E\ \# \text{ trail } S)$
using $\langle \text{trail } S' = M2\ @\ M1 \rangle\ S'\ S\ undefL\ \text{lev-inv}$
by $(\text{cases } M2)\ (\text{auto simp: cdcl}_W\text{-M-level-inv-decomp})$
moreover {
assume $tl\ M2\ @\ M1 = \text{trail } S$
moreover **have** $D + \{\#L'\# \} \in \#$ *clauses* S
using $D-L\ S\ S'\ undefL$ **unfolding** *clauses-def* **by** *auto*
moreover **have** *count-decided* $M1 < \text{backtrack-lvl } S$
using $\text{get-max } S\ S'\ undefL$ **by** *auto*
ultimately obtain L' **where** $L' \in \#$ D **and**
 $\text{get-level } (\text{trail } S)\ L' = \text{count-decided } M1$
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 lev-inv cdcl*_W.*propagate*[*OF propagate*] **by** *blast*
then have *no-dup* $?M'$ **using** $S'\ undefL$ **unfolding** *cdcl*_W-*M-level-inv-def* **by** *auto*
moreover
have *atm-of* $L' \in \text{atm-of ' (lits-of-l } M1)$
using $\langle L' \in \# D \rangle\ \langle M1 \models_{as} CNot\ D \rangle$ **by** $(\text{metis atm-of-uminus image-eqI in-CNot-implies-uminus}(2))$
then have *atm-of* $L' \in \text{atm-of ' (lits-of-l (trail } S))$
using $\langle tl\ M2\ @\ M1 = \text{trail } S \rangle[\text{symmetric}]\ S\ undefL$ **by** *auto*
ultimately have *atm-of* $L \neq \text{atm-of } L'$ **unfolding** *lits-of-def* **by** *auto*
}
ultimately have $\exists L' \in \# D. \text{get-level } (\text{trail } S')\ L' = \text{count-decided } M1$
using $S\ S'\ undefL$ **by** *auto*
}
moreover {
assume $M2 = []$ **and** $M1$: $M1 = \text{Propagated } L\ E\ \# \text{ trail } S$
have *cdcl*_W-*M-level-inv* S'
using *cdcl*_W-*consistent-inv*[*OF - lev-inv*] *cdcl*_W.*propagate*[*OF propagate*] **by** *blast*
then have *count-decided* $M1 = \text{backtrack-lvl } S'$
using $S'\ M1\ undefL$ **unfolding** *cdcl*_W-*M-level-inv-def* **by** $(\text{auto intro: Max-eqI})$
then have *False* **using** *get-max* **by** *auto*
}
ultimately show $\exists L. L \in \# D \wedge \text{get-level } (\text{trail } S')\ L = \text{count-decided } M1$
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* **by** (*force elim!*: *conflictE*)

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** $S = \text{this}$

show 1: *no-more-propagation-to-do* S'

using *propagate-no-more-propagation-to-do*[*of* $S S'$] S **by** *blast*

qed

lemma *cdcl_W-then-exists-cdcl_W-stgy-step*:

assumes

o : *cdcl_W-o* $S S'$ **and**

alien: *no-strange-atm* S **and**

lev : *cdcl_W-M-level-inv* S

shows $\exists S'. \text{cdcl}_W\text{-stgy } S S'$

proof –

obtain S'' **where** *full cdcl_W-cp* $S' S''$

using *always-exists-full-cdcl_W-cp-step* *alien* *cdcl_W-no-strange-atm-inv* *cdcl_W-o-no-more-init-clss*

o *other lev* **by** (*meson cdcl_W-consistent-inv*)

then show ?*thesis*

using *assms* **by** (*metis always-exists-full-cdcl_W-cp-step cdcl_W-stgy.conflict' full-unfold other'*)

qed

lemma *backtrack-no-decomp*:

assumes

S : *conflicting* $S = \text{Some } E$ **and**

LE : $L \in \# E$ **and**

L : *get-level* (*trail* S) $L = \text{backtrack-lvl } S$ **and**

D : *get-maximum-level* (*trail* S) (*remove1-mset* $L E$) $< \text{backtrack-lvl } S$ **and**

bt : *backtrack-lvl* $S = \text{get-maximum-level}$ (*trail* S) E **and**

$M-L$: *cdcl_W-M-level-inv* S

shows $\exists S'. \text{cdcl}_W\text{-o } S S'$

proof –

have $L-D$: *get-level* (*trail* S) $L = \text{get-maximum-level}$ (*trail* S) E

using $L D bt$ **by** (*simp add: get-maximum-level-plus*)

let ? $i = \text{get-maximum-level}$ (*trail* S) (*remove1-mset* $L E$)

obtain $K M1 M2$ **where**

K : (*Decided* $K \# M1, M2$) $\in \text{set } (\text{get-all-ann-decomposition } (\text{trail } S))$ **and**

lev-K: *get-level* (*trail* S) $K = \text{Suc } ?i$

using *backtrack-ex-decomp*[*OF M-L, of ?i*] *D S* **by** *auto*
show *?thesis* **using** *backtrack-rule*[*OF S LE K L, of ?i*] *bt L lev-K bj* **by** (*auto simp: cdcl_W-bj.simps*)
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-ann-decomposition* (*trail S*)) **and**
learned: *cdcl_W-learned-clause S* **and**
level-inv: *cdcl_W-M-level-inv S* **and**
alien: *no-strange-atm S* **and**
no-dup: *distinct-cdcl_W-state S* **and**
confl: *cdcl_W-conflicting S* **and**
confl-k: *conflict-is-false-with-level S*

shows (*conflicting S* = *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*

consider

(*None*) *conflicting S* = *None*
| (*Some-Empty*) *E* **where** *conflicting S* = *Some E* **and** *E* = { $\#$ }
| (*Some*) *E'* **where** *conflicting S* = *Some E'* **and**
conflicting S = *Some (E')* **and** *E' \neq { $\#$ }*

by (*cases conflicting S, simp*) *auto*

then show *?thesis*

proof *cases*

case (*Some-Empty E*)
then have *conflicting S* = *Some { $\#$ }* **by** *auto*
then have *unsatisfiable* (*set-mset* (*init-clss S*))
using *assms(3)* **unfolding** *cdcl_W-learned-clause-def true-clss-clss-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)
then show *?thesis* **using** *Some-Empty* **by** *auto*

next

case *None*

{ **assume** $\neg ?M \models_{\text{asm}} ?N$

have *atm-of* ' (*lits-of-l ?M*) = *atms-of-mm ?N* (**is** *?A* = *?B*)

proof

show *?A* \subseteq *?B* **using** *alien* **unfolding** *no-strange-atm-def* **by** *auto*

show *?B* \subseteq *?A*

proof (*rule ccontr*)

assume $\neg ?B \subseteq ?A$

then obtain *l* **where** *l* \in *?B* **and** *l* \notin *?A* **by** *auto*

then have *undefined-lit ?M* (*Pos l*)

using (*l* \notin *?A*) **unfolding** *lits-of-def* **by** (*auto simp add: defined-lit-map*)

moreover have *conflicting S* = *None*

using *None* **by** *auto*

ultimately have $\exists S'. \text{cdcl}_W\text{-o } S S'$

using *cdcl_W-o.decide decide-rule* (*l* \in *?B*) *no-strange-atm-def*

by (*metis* *literal.sel(1)* *state-eq-def*)

then show *False*

using *termi cdcl_W-then-exists-cdcl_W-stgy-step*[*OF - alien*] *level-inv* **by** *blast*

qed

```

    qed
  obtain  $D$  where  $\neg ?M \models_a D$  and  $D \in \# ?N$ 
    using  $\langle \neg ?M \models_{asm} ?N \rangle$  unfolding lits-of-def true-annots-def Ball-def by auto
  have  $atms\text{-}of\ D \subseteq atm\text{-}of\ \langle lits\text{-}of\text{-}l\ ?M \rangle$ 
    using  $\langle D \in \# ?N \rangle$  unfolding  $\langle atm\text{-}of\ \langle lits\text{-}of\text{-}l\ ?M \rangle = atms\text{-}of\text{-}mm\ ?N \rangle$  atms-of-ms-def
    by (auto simp add: atms-of-def)
  then have  $a1: atm\text{-}of\ \langle set\text{-}mset\ D \subseteq atm\text{-}of\ \langle lits\text{-}of\text{-}l\ (trail\ S) \rangle$ 
    by (auto simp add: atms-of-def lits-of-def)
  have  $total\text{-}over\text{-}m\ (lits\text{-}of\text{-}l\ ?M)\ \{D\}$ 
    using  $\langle atms\text{-}of\ D \subseteq atm\text{-}of\ \langle lits\text{-}of\text{-}l\ ?M \rangle \rangle$ 
    atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set by (fastforce simp: total-over-set-def)
  then have  $?M \models_{as} CNot\ D$ 
    using total-not-true-cls-true-clss-CNot  $\langle \neg trail\ S \models_a D \rangle$  true-annot-def
    true-annots-true-cls by fastforce
  then have False
  proof -
    obtain  $S'$  where
       $f2: full\ cdcl_W\text{-}cp\ S\ S'$ 
      by (meson alien always-exists-full-cdcl_W-cp-step level-inv)
    then have  $S' = S$ 
      using cdcl_W-stgy.conflict'[of S] by (metis (no-types) full-unfold termi)
    then show ?thesis
      using  $f2\ \langle D \in \# init\text{-}class\ S \rangle\ None\ \langle trail\ S \models_{as} CNot\ D \rangle$ 
      clauses-def full-cdcl_W-cp-not-any-negated-init-class by auto
  qed
}
then have  $?M \models_{asm} ?N$  by blast
then show ?thesis
  using None by auto
next
case (Some E') note  $conf = this(1)$  and  $LD = this(2)$  and  $nempty = this(3)$ 
then obtain  $L\ D$  where
   $E'[simp]: E' = D + \{\#L\# \}$  and
   $lev\text{-}L: get\text{-}level\ ?M\ L = ?k$ 
  by (metis (mono-tags) confl-k insert-DiffM2)
let  $?D = D + \{\#L\# \}$ 
have  $?D \neq \{\# \}$  by auto
have  $?M \models_{as} CNot\ ?D$  using confl LD unfolding cdcl_W-conflicting-def by auto
then have  $?M \neq []$  unfolding true-annots-def Ball-def true-annot-def true-cls-def by force
have  $M: ?M = hd\ ?M\ \#\ tl\ ?M$  using  $\langle ?M \neq [] \rangle$  list.collapse by fastforce

have  $g\text{-}k: get\text{-}maximum\text{-}level\ (trail\ S)\ D \leq ?k$ 
  using count-decided-ge-get-maximum-level[of ?M] level-inv
  unfolding cdcl_W-M-level-inv-def
  by auto
{
  assume decided: is-decided (hd ?M)
  then obtain  $k'$  where  $k': k' + 1 = ?k$ 
    using level-inv M unfolding cdcl_W-M-level-inv-def
    by (cases hd (trail S); cases trail S) auto
  obtain  $L'$  where  $L': hd\ ?M = Decided\ L'$  using decided by (cases hd ?M) auto
  have  $*$ :  $\bigwedge list. no\text{-}dup\ list \implies$ 
     $- L \in lits\text{-}of\text{-}l\ list \implies atm\text{-}of\ L \in atm\text{-}of\ \langle lits\text{-}of\text{-}l\ list \rangle$ 
    by (metis atm-of-uminus imageI)
  have  $L'\text{-}L: L' = -L$ 
  proof (rule ccontr)

```

```

assume  $\neg ?thesis$ 
moreover have  $-L \in \text{lit-of-l } ?M$  using confl LD unfolding cdclW-conflicting-def by auto
ultimately have  $\text{get-level } (\text{hd } (\text{trail } S) \# \text{tl } (\text{trail } S)) \text{ } L = \text{get-level } (\text{tl } ?M) \text{ } L$ 
  using cdclW-M-level-inv-decomp(1)[OF level-inv] unfolding consistent-interp-def
  by  $(\text{subst } (\text{asm}) (2) M) (\text{auto simp add: atm-of-eq-atm-of } L')$ 
moreover
  have  $\text{count-decided } (\text{trail } S) = ?k$ 
    using level-inv unfolding cdclW-M-level-inv-def by auto
  then have  $\text{count: count-decided } (\text{tl } (\text{trail } S)) = ?k - 1$ 
    using level-inv unfolding cdclW-M-level-inv-def
    by  $(\text{subst } (\text{asm}) M) (\text{auto simp add: } L')$ 
  then have  $\text{get-level } (\text{tl } ?M) \text{ } L < ?k$ 
    using count-decided-ge-get-level[of L tl ?M] unfolding  $k'[symmetric]$ 
    by auto
  finally show False using lev-L M by auto
qed
have  $L: \text{hd } ?M = \text{Decided } (-L)$  using  $L'-L \text{ } L'$  by auto

have  $\text{get-maximum-level } (\text{trail } S) \text{ } D < ?k$ 
proof (rule ccontr)
  assume  $\neg ?thesis$ 
  then have  $\text{get-maximum-level } (\text{trail } S) \text{ } D = ?k$  using  $M \text{ } g\text{-}k$  unfolding  $L$  by auto
  then obtain  $L''$  where  $L'' \in \# D$  and  $L\text{-}k: \text{get-level } ?M \text{ } L'' = ?k$ 
    using get-maximum-level-exists-lit[of ?k ?M D] unfolding  $k'[symmetric]$  by auto
  have  $L \neq L''$  using no-dup  $\langle L'' \in \# D \rangle$ 
    unfolding distinct-cdclW-state-def LD
    by  $(\text{metis } E' \text{ add.right-neutral add-diff-cancel-right'}$ 
       $\text{distinct-mem-diff-mset union-commute union-single-eq-member})$ 
  have  $L'' = -L$ 
proof (rule ccontr)
  assume  $\neg ?thesis$ 
  then have  $\text{get-level } ?M \text{ } L'' = \text{get-level } (\text{tl } ?M) \text{ } L''$ 
    using  $M \langle L \neq L'' \rangle \text{ get-level-skip-beginning[of } L'' \text{hd } ?M \text{tl } ?M]$  unfolding  $L$ 
    by  $(\text{auto simp: atm-of-eq-atm-of})$ 
  moreover
    have  $d: \text{dropWhile } (\lambda S. \text{atm-of } (\text{lit-of } S) \neq \text{atm-of } L) (\text{tl } (\text{trail } S)) = []$ 
      using level-inv unfolding cdclW-M-level-inv-def apply  $(\text{subst } (\text{asm}) (2) M)$ 
      by  $(\text{auto simp: image-iff } L' \text{ } L'-L)$ 
    have  $\text{get-level } (\text{tl } (\text{trail } S)) \text{ } L = 0$ 
      by  $(\text{auto simp: filter-empty-conv } d)$ 
  moreover
    have  $\text{get-level } (\text{tl } (\text{trail } S)) \text{ } L'' \leq \text{count-decided } (\text{tl } (\text{trail } S))$ 
      by auto
    then have  $\text{get-level } (\text{tl } (\text{trail } S)) \text{ } L'' < \text{backtrack-lvl } S$ 
      using level-inv unfolding cdclW-M-level-inv-def apply  $(\text{subst } (\text{asm}) (5) M)$ 
      by  $(\text{auto simp: image-iff } L' \text{ } L'-L \text{ simp del: count-decided-ge-get-level})$ 
  ultimately show False
  apply  $-$ 
  apply  $(\text{subst } (\text{asm}) M, \text{subst } (\text{asm}) (3) M, \text{subst } (\text{asm}) L')$ 
  using  $L\text{-}k$ 
  apply  $(\text{auto simp: } L' \text{ } L'-L \text{ split: if-splits})$ 
  apply  $(\text{subst } (\text{asm}) (3) M, \text{subst } (\text{asm}) L')$ 
  using  $\langle L'' \neq -L \rangle$  by  $(\text{auto simp: } L' \text{ } L'-L \text{ split: if-splits})$ 
qed
then have taut: tautology  $(D + \{\#L\# \})$ 
  using  $\langle L'' \in \# D \rangle$  by  $(\text{metis add.commute mset-leD mset-le-add-left multi-member-this})$ 

```

```

    tautology-minus)
  have consistent-interp (lits-of-l ?M)
    using level-inv unfolding cdclW-M-level-inv-def by auto
  then have ¬?M ⊨as CNot ?D
    using taut by (metis ⟨L'' = - L⟩ ⟨L'' ∈# D⟩ add.commute consistent-interp-def
      diff-union-cancelR in-CNot-implies-uminus(2) in-diffD multi-member-this)
  moreover have ?M ⊨as CNot ?D
    using confl no-dup LD unfolding cdclW-conflicting-def by auto
  ultimately show False by blast
qed note H = this
have get-maximum-level (trail S) D < get-maximum-level (trail S) (D + {#L#})
  using H by (auto simp: get-maximum-level-plus lev-L max-def)
moreover have backtrack-lvl S = get-maximum-level (trail S) (D + {#L#})
  using H by (auto simp: get-maximum-level-plus lev-L max-def)
ultimately have False
  using backtrack-no-decomp[OF conf - lev-L] level-inv termi
    cdclW-then-exists-cdclW-stgy-step[of S] alien unfolding E'
  by (auto simp add: lev-L max-def)
} note not-is-decided = this

moreover {
  let ?D = D + {#L#}
  have ?D ≠ {#} by auto
  have ?M ⊨as CNot ?D using confl LD unfolding cdclW-conflicting-def by auto
  then have ?M ≠ [] unfolding true-annots-def Ball-def true-annot-def true-cls-def by force
  assume nm: ¬is-decided (hd ?M)
  then obtain L' C where L'C: hd-trail S = Propagated L' C using ⟨trail S ≠ []⟩
    by (cases hd-trail S) auto
  then have hd ?M = Propagated L' C
    using ⟨trail S ≠ []⟩ by fastforce
  then have M: ?M = Propagated L' C # tl ?M
    using ⟨?M ≠ []⟩ list.collapse by fastforce
  then obtain C' where C': C = C' + {#L'#}
    using confl unfolding cdclW-conflicting-def by (metis append-Nil diff-single-eq-union)
  { assume -L' ∈# ?D
    then have Ex (skip S)
      using skip-rule[OF M conf] unfolding E' by auto
    then have False
      using cdclW-then-exists-cdclW-stgy-step[of S] alien level-inv termi
      by (auto dest: cdclW-o.intros cdclW-bj.intros)
  }
  moreover {
    assume L'D: -L' ∈# ?D
    then obtain D' where D': ?D = D' + {#-L'#} by (metis insert-DiffM2)
    then have get-maximum-level (trail S) D' ≤ ?k
      using count-decided-ge-get-maximum-level[of Propagated L' C # tl ?M] M
      level-inv unfolding cdclW-M-level-inv-def by auto
    then have get-maximum-level (trail S) D' = ?k
      ∨ get-maximum-level (trail S) D' < ?k
      using le-neq-implies-less by blast
    moreover {
      assume g-D'-k: get-maximum-level (trail S) D' = ?k
      then have f1: get-maximum-level (trail S) D' = backtrack-lvl S
        using M by auto
      then have Ex (cdclW-o S)
        using f1 resolve-rule[of S L' C , OF ⟨trail S ≠ []⟩ - - conf] conf g-D'-k
    }
  }
}

```

```

    L'C L'D unfolding C' D' E'
    by (fastforce simp add: D' intro: cdclW-o.intros cdclW-bj.intros)
  then have False
    by (meson alien cdclW-then-exists-cdclW-stgy-step termi level-inv)
}
moreover {
  assume a1: get-maximum-level (trail S) D' < ?k
  then have f3: get-maximum-level (trail S) D' < get-level (trail S) (-L')
    using a1 lev-L by (metis D' get-maximum-level-ge-get-level insert-noteq-member
      not-less)
  moreover have backtrack-lvl S = get-level (trail S) L'
    apply (subst M)
    using level-inv unfolding cdclW-M-level-inv-def
    by (subst (asm)(3) M) (auto simp add: cdclW-M-level-inv-decomp)[]
  moreover
    then have get-level (trail S) L' = get-maximum-level (trail S) (D' + {#- L'#})
      using a1 by (auto simp add: get-maximum-level-plus max-def)
    ultimately have False
      using M backtrack-no-decomp[of S - -L', OF conf]
      cdclW-then-exists-cdclW-stgy-step L'D level-inv termi alien
      unfolding D' E' by auto
    }
  ultimately have False by blast
}
ultimately have False by blast
}
ultimately show ?thesis by blast
qed
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 tranclp.r-into-trancl
      tranclp-cdclW-cp-tranclp-cdclW tranclp-trans)
qed

```

lemma *trancpl-cdcl_W-stgy-trancpl-cdcl_W:*
cdcl_W-stgy⁺⁺ S S' \implies cdcl_W⁺⁺ S S'
apply (*induct rule: trancpl.induct*)
using *cdcl_W-stgy-trancpl-cdcl_W apply blast*
by (*meson cdcl_W-stgy-trancpl-cdcl_W trancpl-trans*)

lemma *rtrancpl-cdcl_W-stgy-rtrancpl-cdcl_W:*
*cdcl_W-stgy^{**} S S' \implies cdcl_W^{**} S S'*
using *rtrancpl-unfold[of cdcl_W-stgy S S'] trancpl-cdcl_W-stgy-trancpl-cdcl_W[of S S'] by auto*

lemma *not-empty-get-maximum-level-exists-lit:*
assumes *n: D \neq {#}*
and *max: 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 (($\lambda L. \text{get-level } M \ L$) 'set-mset D)*
using *n max get-maximum-level-exists-lit-of-max-level image-iff*
unfolding *get-maximum-level-def* **by** *force*
then show $\exists L \in \#D. \text{get-level } M \ L = n$ **by** *auto*
qed

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*)
case (*resolve L C M D T*) **note** *tr-S = this(1) and confl = this(4) and LD = this(5) and T = this(7)*
have *uL-not-D: $-L \notin \# \text{remove1-mset } (-L) \ D$*
using *n-d confl unfolding distinct-cdcl_W-state-def distinct-mset-def*
by (*metis distinct-cdcl_W-state-def distinct-mem-diff-mset multi-member-last n-d*)
moreover have *L-not-D: $L \notin \# \text{remove1-mset } (-L) \ D$*
proof (*rule ccontr*)
assume $\neg ?thesis$
then have *L $\in \# D$*
by (*auto simp: in-remove1-mset-neq*)
moreover have *Propagated L C $\# M \models_{as} CNot \ D$*
using *conflicting confl tr-S unfolding cdcl_W-conflicting-def* **by** *auto*
ultimately have $-L \in \text{lits-of-l } (\text{Propagated } L \ C \ \# \ M)$
using *in-CNot-implies-uminus(2)* **by** *blast*
moreover have *no-dup (Propagated L C $\# M$)*
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 ann-lit.sel(2) distinct-consistent-interp*)
qed

ultimately
have *g-D: get-maximum-level (Propagated L C $\# M$) (remove1-mset $(-L) \ D$)*
 $= \text{get-maximum-level } M \ (\text{remove1-mset } (-L) \ D)$
using *get-maximum-level-skip-first[of L remove1-mset $(-L) \ D \ C \ M]$*

by (simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set atms-of-def)
 have lev-L[simp]: get-level M L = 0
 apply (rule atm-of-notin-get-rev-level-eq-0)
 using lev unfolding cdcl_W-M-level-inv-def tr-S by (auto simp: lits-of-def)

 have D: get-maximum-level M (remove1-mset (-L) D) = backtrack-lvl S
 using resolve.hyps(6) LD unfolding tr-S by (auto simp: get-maximum-level-plus max-def g-D)
 have get-maximum-level M (remove1-mset L C) ≤ backtrack-lvl S
 using count-decided-ge-get-maximum-level[of M] lev unfolding tr-S cdcl_W-M-level-inv-def by auto
 then have
 get-maximum-level M (remove1-mset (- L) D #_U remove1-mset L C) =
 backtrack-lvl S
 by (auto simp: get-maximum-level-union-mset get-maximum-level-plus max-def D)
 then show ?case
 using tr-S not-empty-get-maximum-level-exists-lit[of
 remove1-mset (- L) D #_U remove1-mset L C M] T
 by auto
 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 cdcl_W-conflicting-def by auto
 then have -L ∈ lits-of-l M
 using ⟨La ∈# D⟩ in-CNot-implies-uminus(2)[of L D Propagated L C' # M] unfolding La
 by auto
 then show False using lev tr-S unfolding cdcl_W-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
 next
 case backtrack
 then show ?case
 by (auto split: if-split-asm simp: cdcl_W-M-level-inv-decomp lev)
 qed auto

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 rtranclp-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 rtranclp-cdcl_W-cp-propa-or-propa-confl)

lemma *propagate-high-levelE*:

assumes *propagate S T*

obtains $M' N' U k L C$ **where**

state S = ($M', N', U, k, None$) **and**

state T = (*Propagated L* ($C + \{\#L\# \}$) $\# M', N', U, k, None$) **and**

$C + \{\#L\# \} \in \# \text{ local.clauses } S$ **and**

$M' \models_{as} CNot\ C$ **and**

undefined-lit (*trail S*) L

proof –

obtain $E L$ **where**

conf: *conflicting S* = *None* **and**

E: $E \in \# \text{ clauses } S$ **and**

LE: $L \in \# E$ **and**

tr: *trail S* $\models_{as} CNot\ (E - \{\#L\# \})$ **and**

undef: *undefined-lit* (*trail S*) L **and**

T: $T \sim \text{cons-trail}\ (\text{Propagated } L\ E)\ S$

using *assms* **by** (*elim propagateE*) *simp*

obtain $M N U k$ **where**

S: *state S* = ($M, N, U, k, None$)

using *conf* **by** *auto*

show *thesis*

using *that*[*of M N U k L remove1-mset L E*] *S T LE E tr undef*

by *auto*

qed

lemma *cdcl_W-cp-propagate-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**

lits-of-l (*trail S*) $\subseteq \text{set } M$ **and**

init-clss S = N **and**

*propagate** S S'* **and**

learned-clss S = $\{\# \}$

shows $\text{length}\ (\text{trail } S) \leq \text{length}\ (\text{trail } S') \wedge \text{lits-of-l}\ (\text{trail } S') \subseteq \text{set } M$

using *assms*(6,4,5,7)

proof (*induction rule: rtranclp-induct*)

case *base*

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

next

case (*step Y Z*)

note *st* = *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*: $\text{lits-of-l}\ (\text{trail } Y) \subseteq \text{set } M$

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: $M' \models_{as} CNot\ C$ **and**

undefined-lit (*trail Y*) L

using *propa* **by** (*auto elim: propagate-high-levelE*)

have *init-clss S* = *init-clss Y*

using *st* **by** *induction* (*auto elim: propagateE*)

then have [*simp*]: $N' = N$ **using** *NS Y Z* **by** *simp*

have *learned-clss Y* = $\{\# \}$


```

    using st learned by induction (auto elim: propagateE)
  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-clss-def
    by force
  moreover
    have set  $M \models C + \{\#L\}$ 
      using MN C learned Y NS  $\langle \text{init-clss } S = \text{init-clss } Y \rangle \langle \text{learned-clss } Y = \{\#\} \rangle$ 
      unfolding true-clss-def clauses-def by fastforce
    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

```

  assumes propagate** S X
  shows
    rtrancp-propagate-init-clss:  $\text{init-clss } X = \text{init-clss } S$  and
    rtrancp-propagate-learned-clss:  $\text{learned-clss } X = \text{learned-clss } S$ 
  using assms by (induction rule: rtrancp-induct) (auto elim: propagateE)

```

lemma completeness-is-a-full1-propagation:

```

  fixes S :: 'st and M :: 'v literal list
  assumes MN:  $\text{set } M \models_s \text{set-mset } N$ 
  and cons: consistent-interp (set M)
  and tot: total-over-m (set M) (set-mset N)
  and alien: no-strange-atm S
  and learned:  $\text{learned-clss } S = \{\#\}$ 
  and clsS[simp]:  $\text{init-clss } S = N$ 
  and lits:  $\text{lits-of-l } (\text{trail } S) \subseteq \text{set } M$ 
  shows  $\exists S'. \text{propagate** } S S' \wedge \text{full cdcl}_W\text{-cp } S S'$ 

```

proof –

```

  obtain S' where full:  $\text{full cdcl}_W\text{-cp } S S'$ 
    using always-exists-full-cdclW-cp-step alien by blast
  then consider (propa)  $\text{propagate** } S S'$ 
    | (confl)  $\exists X. \text{propagate** } S X \wedge \text{conflict } X S'$ 
    using rtrancp-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

$X: \text{propagate** } S X$ and

$X\text{conf}: \text{conflict } X S'$

by blast

have clsX: $\text{init-clss } X = \text{init-clss } S$

using *X* by (blast dest: rtrancp-propagate-init-clss)

have learnedX: $\text{learned-clss } X = \{\#\}$

using *X* learned by (auto dest: rtrancp-propagate-learned-clss)

obtain *E* where

$E: E \in \# \text{ init-clss } X + \text{learned-clss } X$ and

$\text{Not-}E: \text{trail } X \models_{as} C \text{Not } E$

using *Xconf* by (auto simp add: clauses-def elim!: conflictE)

have lits-of-l (trail *X*) $\subseteq \text{set } M$

using cdcl_W-cp-propagate-completeness[OF assms(1–3) lits - *X* learned] learned by auto

then have MNE: $\text{set } M \models_s C \text{Not } E$

```

    using Not-E
    by (fastforce simp add: true-annots-def true-annot-def true-clss-def true-cls-def)
  have  $\neg$  set  $M \models_s$  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 *rtrancpl-cdcl_W-cp-drop While-trail*

lemma *rtrancpl-propagate-is-trail-append*:
*propagate** S T $\implies \exists c. \text{trail } T = c @ \text{trail } S$*
 by (induction rule: *rtrancpl-induct*) (auto elim: *propagateE*)

lemma *rtrancpl-propagate-is-update-trail*:
*propagate** S T $\implies \text{cdcl}_W$ -M-level-inv S \implies*
init-clss S = init-clss T \wedge learned-clss S = learned-clss T \wedge backtrack-lvl S = backtrack-lvl T
 \wedge conflicting S = conflicting T

proof (induction rule: *rtrancpl-induct*)

```

  case base
  then show ?case unfolding state-eq-def by (auto simp: cdclW-M-level-inv-decomp)
next
  case (step T U) note IH = this(3)[OF this(4)]
  moreover have cdclW-M-level-inv U
    using rtrancpl-cdclW-consistent-inv ⟨propagate** S T⟩ ⟨propagate T U⟩
    rtrancpl-mono[of propagate cdclW] cdclW-cp-consistent-inv propagate'
    rtrancpl-propagate-is-rtrancpl-cdclW step.prem by blast
  then have no-dup (trail U) unfolding cdclW-M-level-inv-def by auto
  ultimately show ?case using ⟨propagate T U⟩ unfolding state-eq-def
    by (fastforce simp: elim: propagateE)
qed

```

lemma *cdcl_W-stgy-strong-completeness-n*:

```

assumes
  MN: set M  $\models_s$  set-mset N and
  cons: consistent-interp (set M) and
  tot: total-over-m (set M) (set-mset N) and
  atm-incl: atm-of ' (set M)  $\subseteq$  atms-of-mm N and
  distM: distinct M and
  length:  $n \leq \text{length } M$ 
shows
   $\exists M' k S. \text{length } M' \geq n \wedge$ 
    lits-of-l  $M' \subseteq \text{set } M \wedge$ 
    no-dup  $M' \wedge$ 
    state  $S = (M', N, \{\#\}, k, \text{None}) \wedge$ 
    cdclW-stgy** (init-state N) S
  using length
proof (induction n)
  case 0
  have state (init-state N) = ( $\square$ , N,  $\{\#\}$ , 0, None)
    by (auto simp: state-eq-def simp del: state-simp)
  moreover have
    0  $\leq \text{length } \square$  and
    lits-of-l  $\square \subseteq \text{set } M$  and
    cdclW-stgy** (init-state N) (init-state N)
    and no-dup  $\square$ 

```

```

    by (auto simp: state-eq-def simp del: state-simp)
ultimately show ?case using state-eq-sym by blast
next
case (Suc n) note IH = this(1) and n = this(2)
then obtain M' k S where
  l-M': length M' ≥ n and
  M': lits-of-l M' ⊆ set M and
  n-d[simp]: no-dup M' and
  S: state S = (M', N, {#}, k, None) and
  st: cdclW-stgy** (init-state N) S
  by auto
have
  M: cdclW-M-level-inv S and
  alien: no-strange-atm S
  using cdclW-M-level-inv-S0-cdclW rtranclp-cdclW-stgy-consistent-inv st apply blast
  using cdclW-M-level-inv-S0-cdclW no-strange-atm-S0 rtranclp-cdclW-no-strange-atm-inv
  rtranclp-cdclW-stgy-rtranclp-cdclW st by blast

{ assume no-step: ¬no-step propagate S
  obtain S' where S': propagate** S S' and full: full cdclW-cp S S'
    using completeness-is-a-full1-propagation[OF assms(1-3), of S] alien M' S
    by (auto simp: comp-def)
  have lev: cdclW-M-level-inv S'
    using M S' rtranclp-cdclW-consistent-inv rtranclp-propagate-is-rtranclp-cdclW by blast
  then have n-d'[simp]: no-dup (trail S')
    unfolding cdclW-M-level-inv-def by auto
  have length (trail S) ≤ length (trail S') ∧ lits-of-l (trail S') ⊆ set M
    using S' full cdclW-cp-propagate-completeness[OF assms(1-3), of S] M' S
    by (auto simp: comp-def)
  moreover
    have full: full1 cdclW-cp S S'
      using full no-step no-step-cdclW-cp-no-conflict-no-propagate(2) unfolding full1-def full-def
      rtranclp-unfold by blast
    then have cdclW-stgy S S' by (simp add: cdclW-stgy.conflict')
  moreover
    have propa: propagate++ S S' using S' full unfolding full1-def by (metis rtranclpD tranclpD)
    have trail S = M'
      using S by (auto simp: comp-def rev-map)
    with propa have length (trail S') > n
      using l-M' propa by (induction rule: tranclp.induct) (auto elim: propagateE)
  moreover
    have stS': cdclW-stgy** (init-state N) S'
      using st cdclW-stgy.conflict'[OF full] by auto
    then have init-clss S' = N
      using stS' rtranclp-cdclW-stgy-no-more-init-clss by fastforce
  moreover
    have
      [simp]: learned-clss S' = {#} and
      [simp]: init-clss S' = init-clss S and
      [simp]: conflicting S' = None
      using tranclp-into-rtranclp[OF ⟨propagate++ S S'⟩] S
      rtranclp-propagate-is-update-trail[of S S'] S M unfolding state-eq-def
      by (auto simp: comp-def)
    have S-S': state S' = (trail S', N, {#}, backtrack-lvl S', None)
      using S by auto
    have cdclW-stgy** (init-state N) S'

```

```

    apply (rule rtrancp.rtrancI-into-rtrancI)
    using st apply simp
    using ⟨cdclW-stgy S S'⟩ by simp
ultimately have ?case
  apply -
  apply (rule exI[of - trail S'], rule exI[of - backtrack-lvl S'], rule exI[of - S'])
  using S-S' by (auto simp: state-eq-def simp del: state-simp)
}
moreover {
  assume no-step: no-step propagate S
  have ?case
  proof (cases length M' ≥ Suc n)
    case True
    then show ?thesis using l-M' M' st M alien S n-d by blast
  next
    case False
    then have n': length M' = n using l-M' by auto
    have no-confI: no-step conflict S
    proof -
      { fix D
        assume D ∈ # N and M' ⊨as CNot D
        then have set M ⊨ D using MN unfolding true-clss-def by auto
        moreover have set M ⊨s CNot D
          using ⟨M' ⊨as CNot D⟩ M'
          by (metis le-iff-sup true-annots-true-clss true-clss-union-increase)
        ultimately have False using cons consistent-CNot-not by blast
      }
    then show ?thesis
    using S by (auto simp: true-clss-def comp-def rev-map
      clauses-def elim!: conflictE)
  qed
  have lenM: length M = card (set M) using distM by (induction M) auto
  have no-dup M' using S M unfolding cdclW-M-level-inv-def by auto
  then have card (lits-of-l M') = length M'
    by (induction M') (auto simp add: lits-of-def card-insert-if)
  then have lits-of-l M' ⊆ set M
    using n M' n' lenM by auto
  then obtain L where L: L ∈ set M and undef-m: L ∉ lits-of-l M' by auto
  moreover have undef: undefined-lit M' L
    using M' Decided-Propagated-in-iff-in-lits-of-l calculation(1,2) cons
    consistent-interp-def by (metis (no-types, lifting) subset-eq)
  moreover have atm-of L ∈ atms-of-mm (init-clss S)
    using atm-incl calculation S by auto
  ultimately
    have dec: decide S (cons-trail (Decided L) (incr-lvl S))
      using decide-rule[of S - cons-trail (Decided L) (incr-lvl S)] S
      by auto
  let ?S' = cons-trail (Decided L) (incr-lvl S)
  have lits-of-l (trail ?S') ⊆ set M using L M' S undef by auto
  moreover have no-strange-atm ?S'
    using alien dec M by (meson cdclW-no-strange-atm-inv decide other)
  ultimately obtain S'' where S'': propagate** ?S' S'' and full: full cdclW-cp ?S' S''
    using completeness-is-a-full1-propagation[OF assms(1-3), of ?S'] S undef
    by auto
  have cdclW-M-level-inv ?S'
    using M dec rtrancp-mono[of decide cdclW] by (meson cdclW-consistent-inv decide other)

```

```

then have lev'': cdclW-M-level-inv S''
  using S'' rtrancpl-cdclW-consistent-inv rtrancpl-propagate-is-rtrancpl-cdclW by blast
then have n-d'': no-dup (trail S'')
  unfolding cdclW-M-level-inv-def by auto
have length (trail ?S') ≤ length (trail S'') ∧ lits-of-l (trail S'') ⊆ set M
  using S'' full cdclW-cp-propagate-completeness[OF assms(1-3), of ?S' S''] L M' S undef
  by simp
then have Suc n ≤ length (trail S'') ∧ lits-of-l (trail S'') ⊆ set M
  using l-M' S undef by auto
moreover
  have cdclW-M-level-inv (cons-trail (Decided L)
    (update-backtrack-lvl (Suc (backtrack-lvl S)) S))
  using S (cdclW-M-level-inv (cons-trail (Decided L) (incr-lvl S))) by auto
then have S'':
  state S'' = (trail S'', N, {#}, backtrack-lvl S'', None)
  using rtrancpl-propagate-is-update-trail[OF S''] S undef n-d'' lev''
  by auto
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

```

theorem 2.9.11 page 84 of Weidenbach's book (with strategy)

lemma cdcl_W-stgy-strong-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**
 atm-incl: atm-of ' (set M) ⊆ atms-of-mm N **and**
 distM: distinct M

shows

∃ M' k S.
 lits-of-l M' = set M ∧
 state S = (M', N, {#}, k, None) ∧
 cdcl_W-stgy** (init-state N) S ∧
 final-cdcl_W-state S

proof –

from cdcl_W-stgy-strong-completeness-n[OF assms, of length M]

obtain M' k T **where**

l: length M ≤ length M' **and**
 M'-M: lits-of-l M' ⊆ set M **and**
 no-dup: no-dup M' **and**
 T: state T = (M', N, {#}, k, None) **and**
 st: cdcl_W-stgy** (init-state N) T
by auto

have card (set M) = length M **using** distM **by** (simp add: distinct-card)

moreover

have cdcl_W-M-level-inv T
using rtrancpl-cdcl_W-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-l 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-l M') using l unfolding lits-of-def by auto
then have set M = lits-of-l 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
ultimately show ?thesis using st T by blast
qed

```

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* ($S :: 'st$) \equiv
 $(\forall M K M' D. M' @ Decided K \# M = \text{trail } S \longrightarrow D \in \# \text{ clauses } S$
 $\longrightarrow \neg M \models_{as} CNot D)$

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*)

case (*decide* $L T$) **note** *confl* = *this*(1) **and** *undef* = *this*(2) **and** $T = \text{this}(4)$

have [simp]: *clauses* $T = \text{clauses } S$

using $T \text{ undef}$ **by** auto

show ?case

proof (*intro allI impI*)

fix $M'' K M' Da$

assume $M'' @ Decided K \# M' = \text{trail } T$

and $D: Da \in \# \text{ local.clauses } T$

then have $tl M'' @ Decided K \# M' = \text{trail } S$

$\vee (M'' = [] \wedge Decided K \# M' = Decided L \# \text{trail } S)$

using $T \text{ undef}$ **by** (*cases* M'') auto

moreover {

assume $tl M'' @ Decided K \# M' = \text{trail } S$

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 $Decided K \# M' = Decided L \# \text{trail } S$

then have $\neg M' \models_{as} CNot Da$ **using** *no-f D confl T* **by** auto

}

ultimately show $\neg M' \models_{as} CNot Da$ **by** *fast*

```

qed
next
  case resolve
  then show ?case using smaller no-f max-lev unfolding no-smaller-confl-def by auto
next
  case skip
  then show ?case using smaller no-f max-lev unfolding no-smaller-confl-def by auto
next
  case (backtrack L D K i M1 M2 T) note confl = this(1) and LD = this(2) and decomp = this(3)
and
  T = this(8)
obtain c where M: trail S = c @ M2 @ Decided K # M1
  using decomp by auto

show ?case
proof (intro allI impI)
  fix M ia K' M' Da
  assume M' @ Decided K' # M = trail T
  then have tl M' @ Decided K' # M = M1
    using T decomp lev by (cases M') (auto simp: cdclW-M-level-inv-decomp)
  let ?S' = (cons-trail (Propagated L D)
    (reduce-trail-to M1 (add-learned-cls D
      (update-backtrack-lvl i (update-conflicting None S)))))
  assume D: Da ∈# clauses T
  moreover{
    assume Da ∈# clauses S
    then have  $\neg M \models_{as} CNot\ Da$  using  $\langle tl\ M' @ Decided\ K' \# M = M1 \rangle M\ confl\ smaller$ 
      unfolding no-smaller-confl-def by auto
  }
  moreover {
    assume Da: Da = D
    have  $\neg M \models_{as} CNot\ Da$ 
    proof (rule ccontr)
      assume  $\neg ?thesis$ 
      then have  $-L \in lits-of-l\ M$ 
        using LD unfolding Da by (simp add: in-CNot-implies-uminus(2))
      then have  $-L \in lits-of-l\ (Propagated\ L\ D \# M1)$ 
        using UnI2  $\langle tl\ M' @ Decided\ K' \# M = M1 \rangle$ 
        by auto
    moreover
      have backtrack S ?S'
        using backtrack-rule[of S] backtrack.hyps
        by (force simp: state-eq-def simp del: state-simp)
      then have cdclW-M-level-inv ?S'
        using cdclW-consistent-inv[OF - lev] other[OF bj] by (auto intro: cdclW-bj.intros)
      then have no-dup (Propagated L D # M1)
        using decomp lev unfolding cdclW-M-level-inv-def by auto
      ultimately show False
        using Decided-Propagated-in-iff-in-lits-of-l defined-lit-map by auto
    qed
  }
  ultimately show  $\neg M \models_{as} CNot\ Da$ 
    using T 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 elim: conflictE)

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  $M'\ K\ M''\ D$ 
  assume  $M': M'' @ Decided\ K \# M' = trail\ S'$ 
  and  $D \in \# clauses\ S'$ 
  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
     $C + \{\#L\#\} \in \# clauses\ S$  and
     $M \models_{as} CNot\ C$  and
    undefined-lit  $M\ L$ 
  using propagate by (auto elim: propagate-high-levelE)
  have  $tl\ M'' @ Decided\ K \# M' = trail\ S$  using  $M'\ S\ S'$ 
  by (metis Pair-inject list.inject list.sel(3) ann-lit.distinct(1) self-append-conv2
    tl-append2)
  then have  $\neg M' \models_{as} CNot\ D$ 
  using  $\langle D \in \# clauses\ S' \rangle\ n-l\ S\ S'\ clauses-def$  unfolding no-smaller-conflict-def by auto
  then show  $\neg M' \models_{as} CNot\ D$  by auto
qed

lemma cdclW-cp-no-smaller-conflict-inv:
  assumes propagate: cdclW-cp  $S\ S'$ 
  and n-l: no-smaller-conflict  $S$ 
  shows no-smaller-conflict  $S'$ 
  using assms
proof (induct rule: cdclW-cp.induct)
  case (conflict'  $S\ S'$ )
  then show ?case using conflict-no-smaller-conflict-inv[of  $S\ S'$ ] by blast
next
  case (propagate'  $S\ S'$ )
  then show ?case using propagate-no-smaller-conflict-inv[of  $S\ S'$ ] by fastforce
qed

lemma rtrancp-cdclW-cp-no-smaller-conflict-inv:
  assumes propagate: cdclW-cp**  $S\ S'$ 
  and n-l: no-smaller-conflict  $S$ 
  shows no-smaller-conflict  $S'$ 
  using assms
proof (induct rule: rtrancp-induct)
  case base
  then show ?case by simp
next
  case (step  $S'\ S''$ )
  then show ?case using cdclW-cp-no-smaller-conflict-inv[of  $S'\ S''$ ] by fast
qed

```



```

lemma trancp-cdclW-cp-no-smaller-conflict-inv:
  assumes propagate: cdclW-cp++ S S'
  and n-l: no-smaller-conflict S
  shows no-smaller-conflict S'
  using assms
proof (induct rule: trancp.induct)
  case (r-into-tranc1 S S')
  then show ?case using cdclW-cp-no-smaller-conflict-inv[of S S'] by blast
next
  case (tranc1-into-tranc1 S S' S'')
  then show ?case using cdclW-cp-no-smaller-conflict-inv[of S' S''] by fast
qed

lemma full-cdclW-cp-no-smaller-conflict-inv:
  assumes full cdclW-cp S S'
  and n-l: no-smaller-conflict S
  shows no-smaller-conflict S'
  using assms unfolding full-def
  using rtrancp-cdclW-cp-no-smaller-conflict-inv[of S S'] by blast

lemma full1-cdclW-cp-no-smaller-conflict-inv:
  assumes full1 cdclW-cp S S'
  and n-l: no-smaller-conflict S
  shows no-smaller-conflict S'
  using assms unfolding full1-def
  using trancp-cdclW-cp-no-smaller-conflict-inv[of S S'] by blast

lemma cdclW-stgy-no-smaller-conflict-inv:
  assumes cdclW-stgy S S'
  and n-l: no-smaller-conflict S
  and conflict-is-false-with-level S
  and cdclW-M-level-inv S
  shows no-smaller-conflict S'
  using assms
proof (induct rule: cdclW-stgy.induct)
  case (conflict' S')
  then show ?case using full1-cdclW-cp-no-smaller-conflict-inv[of S S'] by blast
next
  case (other' S' S'')
  have no-smaller-conflict S'
    using cdclW-o-no-smaller-conflict-inv[OF other'.hyps(1) other'.prems(3,2,1)]
    not-conflict-not-any-negated-init-clss other'.hyps(2) cdclW-cp.simps by auto
  then show ?case using full-cdclW-cp-no-smaller-conflict-inv[of S' S''] other'.hyps by blast
qed

lemma is-conflicting-exists-conflict:
  assumes  $\neg(\forall D \in \#init-clss S' + learned-clss S'. \neg trail S' \models_{as} CNot D)$ 
  and conflicting S' = None
  shows  $\exists S''. conflict S' S''$ 
  using assms clauses-def not-conflict-not-any-negated-init-clss by fastforce

lemma cdclW-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: cdclw-o-induct)
  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-cls-def
        proof (intro allI impI)
          fix x
          assume x: x ∈ {#- L#} | L. L ∈# D
          then obtain L' where L': x = {#- L'#} L' ∈# D by auto
          obtain L'' where L'' ∈# x and L'': lits-of-l (Decided L # ?M) ⊨l L''
            using M-D x T undef unfolding true-annots-def Ball-def true-annot-def CNot-def
              true-cls-def Bex-def by auto
          show ∃ L ∈# x. lits-of-l ?M ⊨l L unfolding Bex-def
            using L'(1) L'(2) ⟨- L ∉# D⟩ ⟨L'' ∈# x⟩
              ⟨lits-of-l (Decided L # trail S) ⊨l L''⟩ by auto
        qed
        then show False using ⟨¬ ?M ⊨as CNot D⟩ by auto
      qed
    have atm-of L ∉ atm-of ' (lits-of-l ?M)
      using undef defined-lit-map unfolding lits-of-def by fastforce
    then have get-level (Decided L # ?M) (-L) = ?k + 1
      using lev unfolding cdclw-M-level-inv-def by auto
    then have -L ∈# D ∧ get-level ?M' (-L) = backtrack-lvl T
      using ⟨-L ∈# D⟩ T undef by auto
    then show ∃ La. La ∈# D ∧ get-level ?M' La = backtrack-lvl T
      by blast
  qed
next
  case resolve
  then show ?case by auto
next
  case skip
  then show ?case by auto
next
  case (backtrack L D K i M1 M2 T) note decomp = this(3) and lev-K = this(7) and T = this(8)
  show ?case

```

```

proof (rule HOL.disjI2, clarify)
  fix Da
  assume Da: Da ∈# clauses T and M-D: trail T ⊨as CNot Da
  obtain c where M: trail S = c @ M2 @ Decided K # M1
    using decomp by auto
  have tr-T: trail T = Propagated L D # M1
    using T decomp lev by (auto simp: cdclW-M-level-inv-decomp)
  have backtrack S T
    using backtrack-rule[of S] backtrack.hyps T
    by (force simp del: state-simp simp: state-eq-def)
  then have lev': cdclW-M-level-inv T
    using cdclW-consistent-inv lev other cdclW-bj.backtrack cdclW-o.bj by blast
  then have - L ∉ lits-of-l M1
    using lev cdclW-M-level-inv-def tr-T unfolding consistent-interp-def by (metis insert-iff
      list.simps(15) lits-of-insert ann-lit.sel(2))
  { assume Da ∈# clauses S
    then have ¬M1 ⊨as CNot Da using no-l M unfolding no-smaller-conflict-def by auto
  }
  moreover {
    assume Da: Da = D
    have ¬M1 ⊨as CNot Da using ⟨- L ∉ lits-of-l M1⟩ unfolding Da
      using backtrack.hyps(2) in-CNot-implies-uminus(2) by auto
  }
  ultimately have ¬M1 ⊨as CNot Da
    using Da T decomp lev by (fastforce simp: cdclW-M-level-inv-decomp)
  then have -L ∈# Da
    using M-D ⟨- L ∉ lits-of-l M1⟩ T unfolding tr-T true-annots-true-cls true-clss-def
    by (auto simp: uminus-lit-swap)
  have no-dup (Propagated L D # M1)
    using lev lev' T decomp unfolding cdclW-M-level-inv-def by auto
  then have L: atm-of L ∉ atm-of ' lits-of-l M1 unfolding lits-of-def by auto
  have get-level (Propagated L D # M1) (-L) = i
    using lev-K lev unfolding cdclW-M-level-inv-def
    by (simp add: M image-Un atm-lit-of-set-lits-of-l)

  then have -L ∈# Da ∧ get-level (trail T) (-L) = backtrack-lvl T
    using ⟨-L ∈# Da⟩ T decomp lev by (auto simp: cdclW-M-level-inv-def)
  then show ∃ La. La ∈# Da ∧ get-level (trail T) La = backtrack-lvl T
    by blast
  qed
qed

```

lemma full1-cdcl_W-cp-exists-conflict-decompose:

assumes

conflict: ∃ D ∈# clauses S. trail S ⊨_{as} CNot D **and**

full: full cdcl_W-cp S U **and**

no-conflict: conflicting S = None **and**

lev: cdcl_W-M-level-inv S

shows ∃ T. propagate** S T ∧ conflict T U

proof -

consider (propa) propagate** S U

| (conflict) T **where** propagate** S T **and** conflict T U

using full **unfolding** full-def **by** (blast dest: rtranclp-cdcl_W-cp-propa-or-propa-conflict)

then show ?thesis

proof cases

case conflict

```

    then show ?thesis by blast
next
case propa
then have conflicting U = None and
  [simp]: learned-clss U = learned-clss S and
  [simp]: init-clss U = init-clss S
  using no-conf rtrancp-propagate-is-update-trail lev by auto
moreover
  obtain D where D: D ∈ #clauses U and
    trS: trail S ⊨as CNot D
    using confl clauses-def by auto
  obtain M where M: trail U = M @ trail S
    using full rtrancp-cdclW-cp-dropWhile-trail unfolding full-def by meson
  have tr-U: trail U ⊨as CNot D
    apply (rule true-annots-mono)
    using trS unfolding M by simp-all
  have ∃ V. conflict U V
    using ⟨conflicting U = None⟩ D clauses-def not-conflict-not-any-negated-init-clss tr-U
    by meson
  then have False using full cdclW-cp.conflict' unfolding full-def by blast
  then show ?thesis by fast
qed
qed

```

lemma full1-cdcl_W-cp-exists-conflict-full1-decompose:

```

assumes
  confl: ∃ D ∈ #clauses S. trail S ⊨as CNot D and
  full: full cdclW-cp S U and
  no-conf: conflicting S = None and
  lev: cdclW-M-level-inv S
shows ∃ T D. propagate** S T ∧ conflict T U
  ∧ trail T ⊨as CNot D ∧ conflicting U = Some D ∧ D ∈ #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 lev rtrancp-propagate-is-update-trail by auto
  have c: learned-clss U = learned-clss T init-clss U = init-clss T
    using conf by (auto elim: conflictE)
  obtain D where trail T ⊨as CNot D ∧ conflicting U = Some D ∧ D ∈ #clauses S
    using conf p c by (fastforce simp: clauses-def elim!: conflictE)
  then show ?thesis
    using propa conf by blast
qed

```

lemma cdcl_W-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-confl S'
    using conflict'.hyps conflict'.prems(1) full1-cdclW-cp-no-smaller-confl-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-confl S''
    using cdclW-stgy-no-smaller-confl-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-confl 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)
    rtranclp-cdclW-co-conflict-ex-lit-of-max-level[of S S']
    unfolding full-def full1-def rtranclp-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'
       $\vee (conflicting\ S' = None \longrightarrow (\forall D \in \#clauses\ S'.\ trail\ S' \models_{as} CNot\ D$ 
         $\longrightarrow (\exists L.\ L \in \#D \wedge get\_level\ (trail\ S')\ L = backtrack\_lvl\ S')))$ 
      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' = 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 rtranclp-cdclW-co-conflict-ex-lit-of-max-level[of S' S''] lev' (no-clause-is-false S')
        by blast
    }
  moreover
    {
      assume c: conflicting S'  $\neq$  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) unfolding full-def by auto
then have  $S' = S''$  using c
  by (induct rule: rtrancp-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  $\neg(\forall D \in \# \text{ clauses } S'. \neg \text{ trail } S' \models_{\text{as}} \text{CNot } D)$ 
    then obtain  $T D$  where
      propagate**  $S' T$  and
      conflict  $T S''$  and
       $D: D \in \# \text{ clauses } S'$  and
       $\text{trail } S'' \models_{\text{as}} \text{CNot } D$  and
      conflicting  $S'' = \text{Some } D$ 
      using full1-cdclW-cp-exists-conflict-full1-decompose[OF - - confl]
      other'(3) lev' by (metis (mono-tags, lifting) conflictE state-eq-trail
        trail-update-conflicting)
    obtain  $M$  where  $M: \text{trail } S'' = M @ \text{trail } S'$  and  $nm: \forall m \in \text{set } M. \neg \text{is-decided } m$ 
      using rtrancp-cdclW-cp-dropWhile-trail other'(3) unfolding full-def by meson
    have btS:  $\text{backtrack-lvl } S'' = \text{backtrack-lvl } S'$ 
      using other'.hyps(3) unfolding full-def by (metis rtrancp-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'.hyps(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  $\text{trail } S' \models_{\text{as}} \text{CNot } D$ 
        moreover then obtain  $L$  where
           $L \in \# D$  and
          lev-L:  $\text{get-level}(\text{trail } S') L = \text{backtrack-lvl } S'$ 
          using D-L  $D$  by blast
        moreover
          have LS':  $-L \in \text{lits-of-l}(\text{trail } S')$ 
            using  $\langle \text{trail } S' \models_{\text{as}} \text{CNot } D \rangle L \in \# D$  in-CNot-implies-uminus(2) by blast
          { fix  $x :: ('v, 'v \text{ clause}) \text{ ann-lit}$  and
             $xb :: ('v, 'v \text{ clause}) \text{ ann-lit}$ 
            assume a1:  $x \in \text{set}(\text{trail } S')$  and
            a2:  $xb \in \text{set } M$  and

```

```

    a3: (λl. atm-of (lit-of l)) ‘ set M ∩ (λl. atm-of (lit-of l)) ‘ set (trail S')
      = {} and
    a4: - L = lit-of x and
    a5: atm-of L = atm-of (lit-of xb)
  moreover have atm-of (lit-of x) = atm-of L
    using a4 by (metis (no-types) atm-of-uminus)
  ultimately have False
    using a5 a3 a2 a1 by auto
}
then have atm-of L ∉ atm-of ‘ lits-of-l 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 ⟨conflicting S'' = Some D⟩ by auto
next
assume ¬trail S' ⊨as CNot D
then obtain L where L ∈ # D and LM: -L ∈ lits-of-l M
  using ⟨trail S'' ⊨as CNot D⟩ unfolding M
  by (auto simp add: true-cls-def M true-annots-def true-annot-def
    split: if-split-asm)
{ fix x :: ('v, 'v clause) ann-lit and
  xb :: ('v, 'v clause) ann-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-l (trail S')
  using nd ⟨L ∈ # D⟩ LM unfolding M by (auto simp add: lits-of-def)
show ?thesis
proof -
  have atm-of L ∈ atm-of ‘ lits-of-l M
    using ⟨-L ∈ lits-of-l M⟩
    by (simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set lits-of-def)
  then have get-level (M @ trail S') L = backtrack-lvl S'
    using lev' LS' nm unfolding cdclW-M-level-inv-def by auto
  then show ?thesis
    using nm ⟨L ∈ # D⟩ ⟨conflicting S'' = Some D⟩
    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 blast
qed

lemma *rtranclp-cdcl_W-stgy-no-smaller-confl-inv*:

assumes

cdcl_W-stgy^{*} *S S'* and

n-l: *no-smaller-confl S* and

cls-false: *conflict-is-false-with-level S* and

lev: *cdcl_W-M-level-inv S* and

no-f: *no-clause-is-false S* and

dist: *distinct-cdcl_W-state S* and

conflicting: *cdcl_W-conflicting S* and

decomp: *all-decomposition-implies-m (init-clss S) (get-all-ann-decomposition (trail S))* and

learned: *cdcl_W-learned-clause S* and

alien: *no-strange-atm S*

shows *no-smaller-confl S' ∧ conflict-is-false-with-level S'*

using *assms(1)*

proof (induct rule: *rtranclp-induct*)

case *base*

then show ?case using *n-l cls-false* by auto

next

case (step *S' S''*) note *st = 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 *cdcl_W-M-level-inv S'*

using *st lev rtranclp-cdcl_W-stgy-rtranclp-cdcl_W*

by (blast intro: *rtranclp-cdcl_W-consistent-inv*)+

moreover have *no-clause-is-false S'*

using *st no-f rtranclp-cdcl_W-stgy-not-non-negated-init-clss* by *presburger*

moreover have *distinct-cdcl_W-state S'*

using *rtanclp-distinct-cdcl_W-state-inv[of S S'] lev rtranclp-cdcl_W-stgy-rtranclp-cdcl_W[OF *st*]*

dist by auto

moreover have *cdcl_W-conflicting S'*

using *rtranclp-cdcl_W-all-inv(6)[of S S'] st alien conflicting decomp dist learned lev*

rtranclp-cdcl_W-stgy-rtranclp-cdcl_W by blast

ultimately show ?case

using *cdcl_W-stgy-no-smaller-confl[OF cdcl] cdcl_W-stgy-ex-lit-of-max-level[OF cdcl]* by fast

qed

Final States are Conclusive

lemma *full-cdcl_W-stgy-final-state-conclusive-non-false*:

fixes *S' :: 'st*

assumes *full*: *full cdcl_W-stgy (init-state N) S'*

and *no-d*: *distinct-mset-mset N*

and *no-empty*: $\forall D \in \#N. D \neq \{\#\}$

shows (*conflicting S' = Some {#} ∧ unsatisfiable (set-mset (init-clss S'))*)

\vee (*conflicting S' = None ∧ trail S' \models_{asm} init-clss S'*)

proof –

let ?*S* = *init-state N*

have

termi: $\forall S''. \neg cdcl_W-stgy S' S''$ and

step: *cdcl_W-stgy*^{*} ?*S S'* using *full unfolding full-def* by auto

moreover have

learned: *cdcl_W-learned-clause S'* and

level-inv: *cdcl_W-M-level-inv S'* and

alien: *no-strange-atm* S' **and**
no-dup: *distinct-cdcl_W-state* S' **and**
conf: *cdcl_W-conflicting* S' **and**
decomp: *all-decomposition-implies-m* (*init-cls* S') (*get-all-ann-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* *elim*!: *conflictE* *simp*: *state-eq-def* *simp* *del*: *state-simp*)
then have *cdcl_W-cp*⁺⁺ S S' **by** *blast*
moreover have *no-step* *cdcl_W-cp* S'
using $\langle \text{conflicting } S' \neq None \rangle$ **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* *elim*: *propagateE* *conflictE*)

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 $S' \implies \text{conflicting } S = \text{Some } \{\#\} \implies \text{False}$

```

by (induction rule: cdclW-cp-induct) (auto elim: propagateE conflictE)

lemma rtrancp-cdclW-cp-conflicting-is-false:
  cdclW-cp++ S S'  $\implies$  conflicting S = Some {#}  $\implies$  False
  apply (induction rule: trancp.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 trancpD)
  unfolding full-def by (metis conflict-with-false-implies-terminated other)

lemma rtrancp-cdclW-stgy-conflicting-is-false:
  cdclW-stgy* S S'  $\implies$  conflicting S = Some {#}  $\implies$  S' = S
  apply (induction rule: rtrancp-induct)
  apply simp
  using cdclW-stgy-conflicting-is-false by blast

lemma full-cdclW-init-clss-with-false-normal-form:
  assumes
     $\forall m \in \text{set } M. \neg \text{is-decided } m$  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-ann-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 rtrancp-cdclW-stgy-conflicting-is-false unfolding full-def cdclW-conflicting-def
    by fastforce
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
  obtain p' where
    p': hd-trail S = Propagated K p' and

```

```

pp': p' = p
using S K by (cases hd-trail S) auto
have conflicting S = Some D
using S E by (cases conflicting S) auto
then have DD: D = D
using S E by auto
consider (D) D = {#} | (D') D ≠ {#} by blast
then show ?case
proof cases
case D
then show ?thesis
using full rtrancpl-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 elim: propagateE conflictE)
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
using S D' K skip-rule unfolding E by fastforce
then have res: no-step resolve S
using ⟨¬lit-of L ∉# D⟩ S D' K unfolding E
by (auto elim!: skipE resolveE)
have full cdclW-cp T T
using sk by (auto intro!: option-full-cdclW-cp elim: skipE)
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' get-level-skip-all-not-decided
get-maximum-level-exists-lit nm not-gr0)
qed
then obtain T where sk: resolve S T
using resolve-rule[of S K p' D] S p' ⟨K ∈# p⟩ D LD
unfolding K' D E pp' by auto
then have res: no-step skip S
using LD S D' K unfolding E
by (auto elim!: skipE resolveE)
have full cdclW-cp T T
using sk by (auto simp: option-full-cdclW-cp elim: resolveE)
then show ?thesis
using sk res by blast

```

```

qed
then have step-s:  $\exists T. \text{cdcl}_W\text{-stgy } S \ T$ 
  using (no-step  $\text{cdcl}_W\text{-cp } S$ ) other' by (meson bj resolve skip)
have get-all-ann-decomposition  $(L \# M) = [([], L\#M)]$ 
  using nm unfolding  $K$  apply (induction  $M$  rule: ann-lit-list-induct, simp)
  by (rename-tac  $L \ xs$ , case-tac  $hd$  (get-all-ann-decomposition  $xs$ ), auto)+
then have no-b: no-step backtrack  $S$ 
  using nm  $S$  by (auto elim: backtrackE)
have no-d: no-step decide  $S$ 
  using  $S \ E$  by (auto elim: decideE)

have full-S-S: full  $\text{cdcl}_W\text{-cp } S \ S$ 
  using  $S \ E$  by (auto simp add: option-full- $\text{cdcl}_W\text{-cp}$ )
then have no-f: no-step (full1  $\text{cdcl}_W\text{-cp}$ )  $S$ 
  unfolding full-def full1-def rtrancpl-unfold by (meson trancplD)
obtain  $T$  where
  s:  $\text{cdcl}_W\text{-stgy } S \ T$  and st:  $\text{cdcl}_W\text{-stgy}^{**} T \ S'$ 
  using full step-s full unfolding full-def by (metis rtrancpl-unfold trancplD)
have resolve  $S \ T \vee \text{skip } S \ T$ 
  using s no-b no-d res-skip full-S-S  $\text{cdcl}_W\text{-cp-state-eq-compatible}$  resolve-unique
  skip-unique unfolding  $\text{cdcl}_W\text{-stgy.simps}$   $\text{cdcl}_W\text{-o.simps}$  full-unfold
  full1-def by (blast dest!: trancplD elim!:  $\text{cdcl}_W\text{-bj.cases}$ )+
then obtain  $D'$  where  $T$ : state  $T = (M, N, U, 0, \text{Some } D')$ 
  using  $S \ E$  by (auto elim!: skipE resolveE simp: state-eq-def simp del: state-simp)

have st-c:  $\text{cdcl}_W^{**} S \ T$ 
  using  $E \ T$  rtrancpl- $\text{cdcl}_W\text{-stgy-rtrancpl-cdcl}_W \ s$  by blast
have  $\text{cdcl}_W\text{-conflicting } T$ 
  using rtrancpl- $\text{cdcl}_W\text{-all-inv}(6)[OF \ st\text{-c inv}(6,5,4,3,2,1)]$  .
show ?thesis
  apply (rule IH[of  $T$ ])
    using rtrancpl- $\text{cdcl}_W\text{-all-inv}(6)[OF \ st\text{-c inv}(6,5,4,3,2,1)]$  apply blast
    using rtrancpl- $\text{cdcl}_W\text{-all-inv}(5)[OF \ st\text{-c inv}(6,5,4,3,2,1)]$  apply blast
    using rtrancpl- $\text{cdcl}_W\text{-all-inv}(4)[OF \ st\text{-c inv}(6,5,4,3,2,1)]$  apply blast
    using rtrancpl- $\text{cdcl}_W\text{-all-inv}(3)[OF \ st\text{-c inv}(6,5,4,3,2,1)]$  apply blast
    using rtrancpl- $\text{cdcl}_W\text{-all-inv}(2)[OF \ st\text{-c inv}(6,5,4,3,2,1)]$  apply blast
    using rtrancpl- $\text{cdcl}_W\text{-all-inv}(1)[OF \ st\text{-c inv}(6,5,4,3,2,1)]$  apply blast
  apply (metis full-def st full)
  using  $T \ E$  apply blast
  apply auto[]
  using nm by simp
qed
qed

lemma full- $\text{cdcl}_W\text{-stgy-final-state-conclusive-is-one-false}$ :
  fixes  $S' :: 'st$ 
  assumes full: full  $\text{cdcl}_W\text{-stgy}$  (init-state  $N$ )  $S'$ 
  and no-d: distinct-mset-mset  $N$ 
  and empty:  $\{\#\} \in \# \ N$ 
  shows conflicting  $S' = \text{Some } \{\#\} \wedge \text{unsatisfiable}(\text{set-mset}(\text{init-clss } S'))$ 
proof -
  let ?S = init-state  $N$ 
  have  $\text{cdcl}_W\text{-stgy}^{**} ?S \ S'$  and no-step  $\text{cdcl}_W\text{-stgy } S'$  using full unfolding full-def by auto
  then have plus-or-eq:  $\text{cdcl}_W\text{-stgy}^{++} ?S \ S' \vee S' = ?S$  unfolding rtrancpl-unfold by auto
  have  $\exists S''. \text{conflict } ?S \ S''$ 
    using empty not-conflict-not-any-negated-init-clss[of init-state  $N$ ] by auto

```

```

then have cdclW-stgy:  $\exists S'. \text{cdcl}_W\text{-stgy } ?S S'$ 
  using cdclW-cp.conflict'[of ?S] conflict-is-full1-cdclW-cp cdclW-stgy.intros(1) by metis
have  $S' \neq ?S$  using  $\langle \text{no-step cdcl}_W\text{-stgy } S' \rangle \text{cdcl}_W\text{-stgy}$  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)  $\langle \text{cdcl}_W\text{-stgy}^{**} ?S S' \rangle \text{converse-rtranclpE}$ )
have st: cdclW** ?S St
  by (simp add: rtranclp-unfold  $\langle \text{cdcl}_W\text{-stgy } ?S St \rangle \text{cdcl}_W\text{-stgy-tranclp-cdcl}_W$ )

have  $\exists T. \text{conflict } ?S T$ 
  using empty not-conflict-not-any-negated-init-clss[of ?S] 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 conf:  $\neg ?thesis$ 
  obtain E where
    ES:  $E \in \# \text{init-clss St}$  and
    E:  $E = \{\#\}$ 
    using empty cls-St by metis
  then have  $\exists T. \text{conflict } St T$ 
    using empty cls-St conflict-rule[of St E] ES conf unfolding E
    by (auto simp: clauses-def dest: )
  then show False using fullSt unfolding full1-def by blast
qed

have 1:  $\forall m \in \text{set } (\text{trail St}). \neg \text{is-decided } m$ 
  using fullSt unfolding full1-def by (auto dest!: tranclp-into-rtranclp
    rtranclp-cdclW-cp-dropWhile-trail)
have 2: full cdclW-stgy St S'
  using  $\langle \text{cdcl}_W\text{-stgy}^{**} St S' \rangle \langle \text{no-step cdcl}_W\text{-stgy } S' \rangle \text{bt}$  unfolding full-def by auto
have 3: all-decomposition-implies-m
  (init-clss St)
  (get-all-ann-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  $\langle \text{conflicting } St \neq \text{None} \rangle$  full-cdclW-init-clss-with-false-normal-form[OF 1, of - - St - -
  S] 2 3 4 5 6 7 8 by (metis bt option.exhaust prod.inject)

moreover have init-clss S' = N
  using  $\langle \text{cdcl}_W\text{-stgy}^{**} (\text{init-state } N) S' \rangle$  rtranclp-cdclW-stgy-no-more-init-clss by fastforce
moreover have unsatisfiable (set-mset N)
  by (meson empty satisfiable-def true-clss-empty true-clss-def)
ultimately show ?thesis by auto
qed

```

theorem 2.9.9 page 83 of Weidenbach's book

```

lemma full-cdclW-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 {#}  $\wedge$  unsatisfiable (set-mset (init-clss S')))
     $\vee$  (conflicting S' = None  $\wedge$  trail S'  $\models_{asm}$  init-clss S')
  using assms full-cdclW-stgy-final-state-conclusive-is-one-false
full-cdclW-stgy-final-state-conclusive-non-false by blast

```

theorem 2.9.9 page 83 of Weidenbach's book

```

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 {#}  $\wedge$  unsatisfiable (set-mset N))
     $\vee$  (conflicting S' = None  $\wedge$  trail S'  $\models_{asm}$  N  $\wedge$  satisfiable (set-mset N))
proof –
  have N: init-clss S' = N
    using full unfolding full-def by (auto dest: rtranclp-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'  $\models_{asm}$  init-clss S'
    using full-cdclW-stgy-final-state-conclusive[OF assms] by auto
  then show ?thesis
    proof cases
      case confl
        then show ?thesis by (auto simp: N)
      next
        case sat
          have cdclW-M-level-inv (init-state N) by auto
          then have cdclW-M-level-inv S'
            using full rtranclp-cdclW-stgy-consistent-inv unfolding full-def by blast
          then have consistent-interp (lits-of-l (trail S')) unfolding cdclW-M-level-inv-def by blast
          moreover have lits-of-l (trail S')  $\models_s$  set-mset (init-clss S')
            using sat(2) by (auto simp add: true-annots-def true-annot-def true-clss-def)
          ultimately have satisfiable (set-mset (init-clss S')) by simp
          then show ?thesis using sat unfolding N by blast
    qed
qed

```

```

end
end
theory CDCL-W-Termination
imports CDCL-W
begin

```

context *conflict-driven-clause-learning_W*
begin

6.1.6 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**

cdcl_W-all-struct-inv $S \longleftrightarrow$
no-strange-atm $S \wedge$
cdcl_W-M-level-inv $S \wedge$
 $(\forall s \in \# \text{ learned-clss } S. \neg \text{tautology } s) \wedge$
distinct-cdcl_W-state $S \wedge$
cdcl_W-conflicting $S \wedge$
all-decomposition-implies-m (*init-clss* S) (*get-all-ann-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-ann-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*)

No Relearning of a clause

lemma *cdcl_W-o-new-clause-learned-is-backtrack-step*:

assumes *learned*: $D \in \# \text{ learned-clss } T$ **and**

new: $D \notin \# \text{ learned-clss } S$ **and**

cdcl_W: *cdcl_W-o* $S \ T$ **and**

lev: *cdcl_W-M-level-inv* S

shows *backtrack* $S \ T \wedge \text{conflicting } S = \text{Some } D$

using *cdcl_W* *lev* *learned* *new*

proof (*induction rule*: *cdcl_W-o-induct*)

case (*backtrack* $L \ C \ K \ i \ M1 \ M2 \ T$) **note** *decomp* = *this*(3) **and** *undef* = *this*(6) **and** $T = \text{this}(8)$

and

$D \cdot T = \text{this}(10)$ **and** $D \cdot S = \text{this}(11)$

then have $D = C$

using *not-gr0* *lev* **by** (*auto simp*: *cdcl_W-M-level-inv-decomp*)

then show ?*case*

using $T \text{ backtrack.hyps}(1-5)$ $\text{backtrack.intros}[OF \text{ backtrack.hyps}(1,2)]$ $\text{backtrack.hyps}(3-7)$

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* - $\langle D \notin \# \text{ learned-clss } S \rangle \langle \text{cdcl}_W\text{-o } S \ S' \rangle$]
 $\langle \text{full } \text{cdcl}_W\text{-cp } S' \ S'' \rangle \text{ lev}$ **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 ∈# learned-clss T)
  case True
  then obtain S' S'' where
    st': cdclW-stgy** S S' and
    bt: backtrack S' S'' and
    confl: conflicting S' = Some D and
    st'': cdclW-stgy** S'' T
  using IH D-S by metis
  have cdclW-stgy++ S'' U
  using st'' o by force
  then show ?thesis
    by (meson bt confl rtrancp-unfold st')
next
case False
have cdclW-M-level-inv T
  using lev rtrancp-cdclW-stgy-consistent-inv st by blast
then obtain S' where
  bt: backtrack T S' and
  st': cdclW-stgy** S' U and
  confl: conflicting T = 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-Decided-lit:
  assumes propagate S S'
  shows Decided K ∈ set (trail S) ⟷ Decided K ∈ set (trail S')
  using assms by (auto elim: propagateE)

```

```

lemma conflict-no-more-Decided-lit:
  assumes conflict S S'
  shows Decided K ∈ set (trail S) ⟷ Decided K ∈ set (trail S')
  using assms by (auto elim: conflictE)

```

```

lemma cdclW-cp-no-more-Decided-lit:
  assumes cdclW-cp S S'
  shows Decided K ∈ set (trail S) ⟷ Decided K ∈ set (trail S')
  using assms apply (induct rule: cdclW-cp.induct)
  using conflict-no-more-Decided-lit propagate-no-more-Decided-lit by auto

```

```

lemma rtrancp-cdclW-cp-no-more-Decided-lit:
  assumes cdclW-cp** S S'
  shows Decided K ∈ set (trail S) ⟷ Decided K ∈ set (trail S')
  using assms apply (induct rule: rtrancp-induct)
  using cdclW-cp-no-more-Decided-lit by blast+

```

```

lemma cdclW-o-no-more-Decided-lit:
  assumes cdclW-o S S' and lev: cdclW-M-level-inv S and ¬decide S S'

```

shows $\text{Decided } K \in \text{set } (\text{trail } S') \longrightarrow \text{Decided } K \in \text{set } (\text{trail } S)$
using *assms*
proof (*induct rule: cdcl_W-o-induct*)
case *backtrack* **note** $\text{decomp} = \text{this}(3)$ **and** $\text{undef} = \text{this}(8)$ **and** $T = \text{this}(9)$
then show *?case* **using** *lev* **by** (*auto simp: cdcl_W-M-level-inv-decomp*)
next
case (*decide* L T)
then show *?case* **using** *decide-rule[OF decide.hyps]* **by** *blast*
qed *auto*

lemma *cdcl_W-new-decided-at-beginning-is-decide:*
assumes *cdcl_W-stgy* S S' **and**
lev: cdcl_W-M-level-inv S **and**
trail $S' = M' @ \text{Decided } L \# M$ **and**
trail $S = M$
shows $\exists T. \text{decide } S \ T \wedge \text{no-step } \text{cdcl}_W\text{-cp } S$
using *assms*
proof (*induct rule: cdcl_W-stgy.induct*)
case (*conflict'* S') **note** $st = \text{this}(1)$ **and** $\text{no-dup} = \text{this}(2)$ **and** $S' = \text{this}(3)$ **and** $S = \text{this}(4)$
have *cdcl_W-M-level-inv* S'
using *full1-cdcl_W-cp-consistent-inv no-dup st* **by** *blast*
then have $\text{Decided } L \in \text{set } (\text{trail } S')$ **and** $\text{Decided } L \notin \text{set } (\text{trail } S)$
using *no-dup unfolding* S S' *cdcl_W-M-level-inv-def* **by** (*auto simp add: rev-image-eqI*)
then have *False*
using *st rtranclp-cdcl_W-cp-no-more-Decided-lit[of S S']*
unfolding *full1-def rtranclp-unfold* **by** *blast*
then show *?case* **by** *fast*
next
case (*other'* T U) **note** $o = \text{this}(1)$ **and** $ns = \text{this}(2)$ **and** $st = \text{this}(3)$ **and** $\text{no-dup} = \text{this}(4)$ **and**
 $S' = \text{this}(5)$ **and** $S = \text{this}(6)$
have *cdcl_W-M-level-inv* U
by (*metis (full-types) lev cdcl_W.simps cdcl_W-consistent-inv full-def o*
other'.hyps(3) rtranclp-cdcl_W-cp-consistent-inv)
then have $\text{Decided } L \in \text{set } (\text{trail } U)$ **and** $\text{Decided } L \notin \text{set } (\text{trail } S)$
using *no-dup unfolding* S S' *cdcl_W-M-level-inv-def* **by** (*auto simp add: rev-image-eqI*)
then have $\text{Decided } L \in \text{set } (\text{trail } T)$
using *st rtranclp-cdcl_W-cp-no-more-Decided-lit* **unfolding** *full-def* **by** *blast*
then show *?case*
using *cdcl_W-o-no-more-Decided-lit[OF o] (Decided L ∉ set (trail S)) ns lev* **by** *meson*
qed

lemma *cdcl_W-o-is-decide:*
assumes *cdcl_W-o* S T **and** *lev: cdcl_W-M-level-inv* S
trail $T = \text{drop } (\text{length } M_0) \ M' @ \text{Decided } L \# H @ M$ **and**
 $\neg (\exists M'. \text{trail } S = M' @ \text{Decided } L \# H @ M)$
shows *decide* S T
using *assms*
proof (*induction rule: cdcl_W-o-induct*)
case (*backtrack* L D K i $M1$ $M2$ T)
then obtain c **where** $\text{trail } S = c @ M2 @ \text{Decided } K \# M1$
by *auto*
show *?case*
using *backtrack lev*
apply (*cases drop (length M₀) M'*)
apply (*auto simp: cdcl_W-M-level-inv-decomp*)
using $\langle \text{trail } S = c @ M2 @ \text{Decided } K \# M1 \rangle$

```

    by (auto simp: cdclW-M-level-inv-decomp)
next
  case decide
  show ?case using decide-rule[of S] decide(1-4) by auto
qed auto

lemma rtrancpl-cdclW-new-decided-at-beginning-is-decide:
  assumes cdclW-stgy** R U and
  trail U = M' @ Decided L # H @ M and
  trail R = M and
  cdclW-M-level-inv R
  shows
     $\exists S T T'. \text{cdcl}_W\text{-stgy}^{**} R S \wedge \text{decide } S T \wedge \text{cdcl}_W\text{-stgy}^{**} T U \wedge \text{cdcl}_W\text{-stgy}^{**} S U \wedge$ 
     $\text{no-step } \text{cdcl}_W\text{-cp } S \wedge \text{trail } T = \text{Decided } L \# H @ M \wedge \text{trail } S = H @ M \wedge \text{cdcl}_W\text{-stgy } S T' \wedge$ 
     $\text{cdcl}_W\text{-stgy}^{**} T' U$ 
  using assms
proof (induct arbitrary: M H M' i rule: rtrancpl-induct)
  case base
  then show ?case by auto
next
  case (step T U) note st = this(1) and IH = this(3) and s = this(2) and
    U = this(4) and S = this(5) and lev = this(6)
  show ?case
  proof (cases  $\exists M'. \text{trail } T = M' @ \text{Decided } L \# H @ M$ )
    case False
    with s show ?thesis using U s st S
  proof induction
    case (conflict' W) note cp = this(1) and nd = this(2) and W = this(3)
    then obtain M0 where trail W = M0 @ trail T and ndecided:  $\forall l \in \text{set } M_0. \neg \text{is-decided } l$ 
      using rtrancpl-cdclW-cp-dropWhile-trail unfolding full1-def rtrancpl-unfold by meson
    then have MV:  $M' @ \text{Decided } L \# H @ M = M_0 @ \text{trail } T$  unfolding W by simp
    then have V: trail T = drop (length M0) (M' @ Decided L # H @ M)
      by auto
    have takeWhile (Not o is-decided) M' = M0 @ takeWhile (Not o is-decided) (trail T)
      using arg-cong[OF MV, of takeWhile (Not o is-decided)] ndecided
      by (simp add: takeWhile-tail)
    from arg-cong[OF this, of length] have length M0 ≤ length M'
      unfolding length-append by (metis (no-types, lifting) Nat.le-trans le-add1
        length-takeWhile-le)
    then have False using nd V by auto
    then show ?case by fast
  next
    case (other' T' U) note o = this(1) and ns = this(2) and cp = this(3) and nd = this(4)
      and U = this(5) and st = this(6)
    obtain M0 where trail U = M0 @ trail T' and ndecided:  $\forall l \in \text{set } M_0. \neg \text{is-decided } l$ 
      using rtrancpl-cdclW-cp-dropWhile-trail cp unfolding full-def by meson
    then have MV:  $M' @ \text{Decided } L \# H @ M = M_0 @ \text{trail } T'$  unfolding U by simp
    then have V: trail T' = drop (length M0) (M' @ Decided L # H @ M)
      by auto
    have takeWhile (Not o is-decided) M' = M0 @ takeWhile (Not o is-decided) (trail T')
      using arg-cong[OF MV, of takeWhile (Not o is-decided)] ndecided
      by (simp add: takeWhile-tail)
    from arg-cong[OF this, of length] have length M0 ≤ length M'
      unfolding length-append by (metis (no-types, lifting) Nat.le-trans le-add1
        length-takeWhile-le)
    then have tr-T': trail T' = drop (length M0) M' @ Decided L # H @ M using V by auto
  end
end

```

then have LT' : Decided $L \in \text{set } (\text{trail } T')$ by auto
 moreover
 have $\text{cdcl}_W\text{-}M\text{-level-inv } T$
 using $\text{lev } r\text{trancp-cdcl}_W\text{-stgy-consistent-inv step.hyps}(1)$ by blast
 then have decide $T T'$ using $\text{ond tr-}T' \text{cdcl}_W\text{-o-is-decide}$ by metis
 ultimately have decide $T T'$ using $\text{cdcl}_W\text{-o-no-more-Decided-lit}[OF o]$ by blast
 then have 1: $\text{cdcl}_W\text{-stgy}^{**} R T$ and 2: decide $T T'$ and 3: $\text{cdcl}_W\text{-stgy}^{**} T' U$
 using $\text{st other'}.prems(4)$
 by $(\text{metis } \text{cdcl}_W\text{-stgy.conflict' cp full-unfold r-into-rtrancp } r\text{trancp.rtrancp-refl}) +$
 have $[\text{simp}]$: drop $(\text{length } M_0) M' = []$
 using $\langle \text{decide } T T' \rangle \langle \text{Decided } L \in \text{set } (\text{trail } T') \rangle \text{nd tr-}T'$
 by $(\text{auto simp add: Cons-eq-append-conv elim: decideE})$
 have T' : drop $(\text{length } M_0) M' @ \text{Decided } L \# H @ M = \text{Decided } L \# \text{trail } T$
 using $\langle \text{decide } T T' \rangle \langle \text{Decided } L \in \text{set } (\text{trail } T') \rangle \text{nd tr-}T'$
 by $(\text{auto elim: decideE})$
 have $\text{trail } T' = \text{Decided } L \# \text{trail } T$
 using $\langle \text{decide } T T' \rangle \langle \text{Decided } L \in \text{set } (\text{trail } T') \rangle \text{tr-}T'$
 by $(\text{auto elim: decideE})$
 then have 5: $\text{trail } T' = \text{Decided } L \# H @ M$
 using $\text{append.simps}(1) \text{list.sel}(3) \text{local.other'}(5) \text{tl-append2}$ by $(\text{simp add: tr-}T')$
 have 6: $\text{trail } T = H @ M$
 by $(\text{metis } (\text{no-types}) \langle \text{trail } T' = \text{Decided } L \# \text{trail } T \rangle$
 $\langle \text{trail } T' = \text{drop } (\text{length } M_0) M' @ \text{Decided } L \# H @ M \rangle \text{append-Nil list.sel}(3) \text{nd}$
 $\text{tl-append2})$
 have 7: $\text{cdcl}_W\text{-stgy}^{**} T U$ using $\text{other'}.prems(4) \text{st}$ by auto
 have 8: $\text{cdcl}_W\text{-stgy } T U \text{cdcl}_W\text{-stgy}^{**} U U$
 using $\text{cdcl}_W\text{-stgy.other'}[OF \text{other'}(1-3)]$ by simp-all
 show ?case apply $(\text{rule exI}[of - T], \text{rule exI}[of - T'], \text{rule exI}[of - U])$
 using $\text{ns } 1 \ 2 \ 3 \ 5 \ 6 \ 7 \ 8$ by fast
 qed
 next
 case True
 then obtain M' where T : $\text{trail } T = M' @ \text{Decided } L \# H @ M$ by metis
 from $\text{IH}[OF \text{this } S \text{lev}]$ obtain $S' S'' S'''$ where
 1: $\text{cdcl}_W\text{-stgy}^{**} R S'$ and
 2: decide $S' S''$ and
 3: $\text{cdcl}_W\text{-stgy}^{**} S'' T$ and
 4: $\text{no-step } \text{cdcl}_W\text{-cp } S'$ and
 6: $\text{trail } S'' = \text{Decided } L \# H @ M$ and
 7: $\text{trail } S' = H @ M$ and
 8: $\text{cdcl}_W\text{-stgy}^{**} S' T$ and
 9: $\text{cdcl}_W\text{-stgy } S' S'''$ and
 10: $\text{cdcl}_W\text{-stgy}^{**} S''' T$
 by blast
 have $\text{cdcl}_W\text{-stgy}^{**} S'' U$ using $s \langle \text{cdcl}_W\text{-stgy}^{**} S'' T \rangle$ by auto
 moreover have $\text{cdcl}_W\text{-stgy}^{**} S' U$ using $8 s$ by auto
 moreover have $\text{cdcl}_W\text{-stgy}^{**} S''' U$ using $10 s$ by auto
 ultimately show ?thesis apply – apply $(\text{rule exI}[of - S'], \text{rule exI}[of - S''])$
 using $1 \ 2 \ 4 \ 6 \ 7 \ 8 \ 9$ by blast
 qed
 qed
 lemma $r\text{trancp-cdcl}_W\text{-new-decided-at-beginning-is-decide'}$:
 assumes $\text{cdcl}_W\text{-stgy}^{**} R U$ and
 $\text{trail } U = M' @ \text{Decided } L \# H @ M$ and
 $\text{trail } R = M$ and

$cdcl_W\text{-}M\text{-level-inv } R$
shows $\exists y y'. cdcl_W\text{-}stgy^{**} R y \wedge cdcl_W\text{-}stgy y y' \wedge \neg (\exists c. trail y = c @ Decided L \# H @ M)$
 $\wedge (\lambda a b. cdcl_W\text{-}stgy a b \wedge (\exists c. trail a = c @ Decided L \# H @ M))^{**} y' U$
proof –
fix T'
obtain $S' T T'$ **where**
 $st: cdcl_W\text{-}stgy^{**} R S'$ **and**
 $decide S' T$ **and**
 $TU: cdcl_W\text{-}stgy^{**} T U$ **and**
 $no\text{-}step cdcl_W\text{-}cp S'$ **and**
 $trT: trail T = Decided L \# H @ M$ **and**
 $trS': trail S' = H @ M$ **and**
 $S'U: cdcl_W\text{-}stgy^{**} S' U$ **and**
 $S'T': cdcl_W\text{-}stgy S' T'$ **and**
 $T'U: cdcl_W\text{-}stgy^{**} T' U$
using $rtranclp\text{-}cdcl_W\text{-}new\text{-}decided\text{-}at\text{-}beginning\text{-}is\text{-}decide[OF assms]$ **by** *blast*
have $n: \neg (\exists c. trail S' = c @ Decided L \# H @ M)$ **using** trS' **by** *auto*
show *?thesis*
using $rtranclp\text{-}trans[OF st]$ $rtranclp\text{-}exists\text{-}last\text{-}with\text{-}prop[of cdcl_W\text{-}stgy S' T' -$
 $\lambda a -. \neg (\exists c. trail a = c @ Decided L \# H @ M), OF S'T' T'U n]$
by *meson*
qed

lemma *beginning-not-decided-invert*:
assumes $A: M @ A = M' @ Decided K \# H$ **and**
 $nm: \forall m \in set M. \neg is\text{-}decided m$
shows $\exists M. A = M @ Decided K \# H$
proof –
have $A = drop (length M) (M' @ Decided K \# H)$
using $arg\text{-}cong[OF A, of drop (length M)]$ **by** *auto*
moreover **have** $drop (length M) (M' @ Decided K \# H) = drop (length M) M' @ Decided K \# H$
using nm **by** (*metis* (*no-types*, *lifting*) A *drop-Cons'* *drop-append ann-lit.disc(1)* *not-gr0*
 $nth\text{-}append nth\text{-}append\text{-}length nth\text{-}mem zero\text{-}less\text{-}diff$)
finally **show** *?thesis* **by** *fast*
qed

lemma *cdcl_W-stgy-trail-has-new-decided-is-decide-step*:
assumes $cdcl_W\text{-}stgy S T$
 $\neg (\exists c. trail S = c @ Decided L \# H @ M)$ **and**
 $(\lambda a b. cdcl_W\text{-}stgy a b \wedge (\exists c. trail a = c @ Decided L \# H @ M))^{**} T U$ **and**
 $\exists M'. trail U = M' @ Decided L \# H @ M$ **and**
 $lev: cdcl_W\text{-}M\text{-level-inv } S$
shows $\exists S'. decide S S' \wedge full cdcl_W\text{-}cp S' T \wedge no\text{-}step cdcl_W\text{-}cp S$
using $assms(3,1,2,4,5)$
proof *induction*
case (*step* $T U$)
then **show** *?case* **by** *fastforce*
next
case *base*
then **show** *?case*
proof (*induction rule: cdcl_W-stgy.induct*)
case (*conflict'* T) **note** $cp = this(1)$ **and** $nd = this(2)$ **and** $M' = this(3)$ **and** $no\text{-}dup = this(3)$
then **obtain** M' **where** $M': trail T = M' @ Decided L \# H @ M$ **by** *metis*
obtain M'' **where** $M'': trail T = M'' @ trail S$ **and** $nm: \forall m \in set M''. \neg is\text{-}decided m$
using cp **unfolding** *full1-def*
by (*metis* $rtranclp\text{-}cdcl_W\text{-}cp\text{-}drop While\text{-}trail'$ $tranclp\text{-}into\text{-}rtranclp$)

```

have False
  using beginning-not-decided-invert[of M'' trail S M' L H @ M] M' nm nd unfolding M''
  by fast
then show ?case by fast
next
case (other' T U') note o = this(1) and ns = this(2) and cp = this(3) and nd = this(4)
  and trU' = this(5)
have cdclW-cp** T U' using cp unfolding full-def by blast
from rtrancp-cdclW-cp-dropWhile-trail[OF this]
have  $\exists M'. \text{trail } T = M' @ \text{Decided } L \# H @ M$ 
  using trU' beginning-not-decided-invert[of - trail T - L H @ M] by metis
then obtain M' where M': trail T = M' @ Decided L # H @ M
  by auto
with o lev nd cp ns
show ?case
proof (induction rule: cdclW-o-induct)
  case (decide L) note dec = this(1) and cp = this(5) and ns = this(4)
  then have decide S (cons-trail (Decided L) (incr-lvl S))
    using decide.hyps decide.intros[of S] by force
  then show ?case using cp decide.premis by (meson decide-state-eq-compatible ns state-eq-ref
    state-eq-sym)
next
case (backtrack L' D K j M1 M2 T) note decomp = this(3) and undef = this(8) and
  T = this(9) and trT = this(13)
obtain MS3 where MS3: trail S = MS3 @ M2 @ Decided K # M1
  using get-all-ann-decomposition-exists-prepend[OF decomp] by metis
have tl (M' @ Decided L # H @ M) = tl M' @ Decided L # 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' @ Decided L # H @ M
  using arg-cong[OF trT[simplified], of tl] T decomp undef lev
  by (simp add: cdclW-M-level-inv-decomp)
have False using nd MS3 T undef decomp unfolding M'' by auto
then show ?case by fast
qed auto
qed
qed

```

lemma rtrancp-cdcl_W-stgy-with-trail-end-has-trail-end:

```

assumes (λa b. cdclW-stgy a b ∧ (∃ c. trail a = c @ Decided L # H @ M))** T U and
  ∃ M'. trail U = M' @ Decided L # H @ M
shows ∃ M'. trail T = M' @ Decided L # H @ M
using assms by (induction rule: rtrancp-induct) auto

```

lemma remove1-mset-eq-remove1-mset-same:

```

remove1-mset L D = remove1-mset L' D ⇒ L ∈# D ⇒ L = L'
by (metis diff-single-trivial insert-DiffM multi-drop-mem-not-eq single-eq-single
  union-right-cancel)

```

lemma cdcl_W-o-cannot-learn:

```

assumes
  cdclW-o y z and
  lev: cdclW-M-level-inv y and
  M: trail y = c @ Decided Kh # H and
  DL: D ∉# learned-clss y and
  LD: L ∈# D and
  DH: atms-of (remove1-mset L D) ⊆ atm-of ' lits-of-l H and

```

$LH: atm\text{-}of\ L \notin atm\text{-}of\ ' lits\text{-}of\text{-}l\ H$ **and**
 $learned: \forall T. \text{conflicting } y = \text{Some } T \longrightarrow \text{trail } y \models_{as} CNot\ T$ **and**
 $z: \text{trail } z = c' @ Decided\ Kh \# H$
shows $D \notin \# learned\text{-}clss\ z$
using $assms(1-2)\ M\ DL\ DH\ LH\ learned\ z$
proof (*induction rule: $cdcl_W\text{-}o\text{-}induct$*)
case ($backtrack\ L'\ D'\ K\ j\ M1\ M2\ T$) **note** $confl = this(1)$ **and** $LD' = this(2)$ **and** $decomp = this(3)$
and $levL = this(4)$ **and** $levD = this(5)$ **and** $j = this(6)$ **and** $lev\text{-}K = this(7)$ **and** $T = this(8)$ **and**
 $z = this(15)$
def $i \equiv get\text{-}level\ (\text{trail } T)\ Kh$
have $levT: cdcl_W\text{-}M\text{-}level\text{-}inv\ T$
using $backtrack\text{-}rule[OF\ confl\ LD'\ decomp\ levL\ levD\ -\ T]\ lev\text{-}K\ j\ lev$
by ($metis\ Suc\text{-}eq\text{-}plus1\ cdcl_W.simps\ cdcl_W\text{-}bj.simps\ cdcl_W\text{-}consistent\text{-}inv\ cdcl_W\text{-}o.simps$)
obtain $M3$ **where** $M3: \text{trail } y = M3 @ M2 @ Decided\ K \# M1$
using $decomp\ get\text{-}all\text{-}ann\text{-}decomposition\text{-}exists\text{-}prepend$ **by** $metis$
have $c' @ Decided\ Kh \# H = \text{Propagated } L'\ D' \# \text{trail } (\text{reduce}\text{-}trail\text{-}to\ M1\ y)$
using $z\ decomp\ T\ lev$ **by** ($force\ simp: cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}def$)
then obtain d **where** $d: M1 = d @ Decided\ Kh \# H$
by ($metis\ (no\text{-}types)\ decomp\ in\text{-}get\text{-}all\text{-}ann\text{-}decomposition\text{-}trail\text{-}update\text{-}trail\ list.inject\ list.sel(3)\ ann\text{-}lit.distinct(1)\ self\text{-}append\ conv2\ tl\text{-}append2$)

have $atm\text{-}of\ Kh \notin atm\text{-}of\ ' lits\text{-}of\text{-}l\ c'$
using $levT\ unfolding\ cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}def\ z$
by ($auto\ simp: atm\text{-}lit\text{-}of\text{-}set\text{-}lits\text{-}of\text{-}l$)
then have $count\text{-}H: count\text{-}decided\ H = i - 1\ i > 0$
unfolding $z\ i\text{-}def$ **by** $auto$
have $n\text{-}d\text{-}y: no\text{-}dup\ (\text{trail } y)$ **and** $bt\text{-}y: backtrack\text{-}lvl\ y = count\text{-}decided\ (\text{trail } y)$
using $lev\ unfolding\ cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}def$ **by** $auto$
have $tr\text{-}T: \text{trail } T = \text{Propagated } L'\ D' \# M1$
using $decomp\ T\ n\text{-}d\text{-}y$ **by** $auto$

show $?case$
proof
assume $D \in \# learned\text{-}clss\ T$
then have $DLD': D = D'$
using $DL\ T\ neq0\text{-}conv\ decomp\ n\text{-}d\text{-}y$ **by** $fastforce$
have $L\text{-}cKh: atm\text{-}of\ L \in atm\text{-}of\ ' lits\text{-}of\text{-}l\ (c @ [Decided\ Kh])$
using $LH\ learned\ M\ DLD'[symmetric]\ confl\ LD'\ LD$

apply ($auto\ simp\ add: image\text{-}iff\ dest!: in\text{-}CNot\text{-}implies\text{-}uminus$)
apply ($metis\ atm\text{-}of\text{-}uminus$) **done**
then consider (Lc) $atm\text{-}of\ L \in atm\text{-}of\ ' lits\text{-}of\text{-}l\ c$ **and** $atm\text{-}of\ L \neq atm\text{-}of\ Kh \mid$
 $(LKh)\ atm\text{-}of\ L = atm\text{-}of\ Kh$ **and** $atm\text{-}of\ L \notin atm\text{-}of\ ' lits\text{-}of\text{-}l\ c$
using $n\text{-}d\text{-}y\ M$ **by** ($auto\ simp: atm\text{-}lit\text{-}of\text{-}set\text{-}lits\text{-}of\text{-}l$)
then have $lev\text{-}L\text{-}c\text{-}Kh: get\text{-}level\ (c @ [Decided\ Kh])\ L \geq 1$
by $cases\ auto$
have $get\text{-}level\ (\text{trail } y)\ L = get\text{-}level\ (c @ [Decided\ Kh])\ L + count\text{-}decided\ H$
using $get\text{-}rev\text{-}level\text{-}skip\text{-}end[OF\ L\text{-}cKh, of\ H]$ **unfolding** M **by** $simp$
then have $get\text{-}level\ (\text{trail } y)\ L \geq i$
using $count\text{-}H\ lev\text{-}L\text{-}c\text{-}Kh$ **by** $linarith$
then have $i\text{-}le\text{-}bt\text{-}y: i \leq backtrack\text{-}lvl\ y$
using $cdcl_W\text{-}M\text{-}level\text{-}inv\text{-}get\text{-}level\text{-}le\text{-}backtrack\text{-}lvl[OF\ lev, of\ L]$ **by** $linarith$
have $DD'[simp]: remove1\text{-}mset\ L\ D = D' - \{\#L'\}$
proof ($rule\ ccontr$)
assume $DD': \neg ?thesis$
then have $L' \in \# remove1\text{-}mset\ L\ D$ **using** $DLD'\ LD$ **by** ($metis\ LD'\ in\text{-}remove1\text{-}mset\text{-}neg$)

then have $\text{get-level } (\text{trail } y) \ L' \leq \text{get-maximum-level } (\text{trail } y) \ (\text{remove1-mset } L \ D)$
using $\text{get-maximum-level-ge-get-level}$ **by** *blast*
moreover
have $\forall x \in \text{atms-of } (\text{remove1-mset } L \ D). \ x \notin \text{atm-of } \text{'lits-of-l } (c \ @ \ \text{Decided } Kh \ \# \ [])$
using $DH \ n\text{-d-y}$ **unfolding** M **by** $(\text{auto simp: atm-lit-of-set-lits-of-l})$
from $\text{get-maximum-level-skip-beginning}[OF \ \text{this}, \ \text{of } H]$
have $\text{get-maximum-level } (\text{trail } y) \ (\text{remove1-mset } L \ D) =$
 $\text{get-maximum-level } H \ (\text{remove1-mset } L \ D)$
unfolding M **by** $(\text{simp add: get-maximum-level-skip-beginning})$
moreover
have $\text{atm-of } Kh \notin \text{atm-of } \text{'lits-of-l } c'$
using levT **unfolding** $\text{cdcl}_W\text{-M-level-inv-def } z$
by $(\text{auto simp: atm-lit-of-set-lits-of-l})$
then have $\text{count-decided } H < i$
unfolding $i\text{-def } z$ **by** *auto*
then have $0 < i - \text{count-decided } H$
by *presburger*
ultimately have $\text{get-maximum-level } (\text{trail } y) \ (\text{remove1-mset } L \ D) < i$
by $(\text{metis } (\text{no-types}) \ \text{count-decided-ge-get-maximum-level} \ \text{diff-is-0-eq} \ \text{diff-le-mono2} \ \text{not-le})$
moreover
have $L \in \# \ \text{remove1-mset } L' \ D'$
using $DLD'[symmetric] \ DD' \ LD$ **by** $(\text{metis in-remove1-mset-neq})$
then have $\text{get-maximum-level } (\text{trail } y) \ (\text{remove1-mset } L' \ D') \geq$
 $\text{get-level } (\text{trail } y) \ L$
using $\text{get-maximum-level-ge-get-level}$ **by** *blast*
moreover
have $\text{get-maximum-level } (\text{trail } y) \ (\text{remove1-mset } L' \ D')$
 $< \text{get-level } (\text{trail } y) \ L$
using $\langle \text{get-level } (\text{trail } y) \ L' \leq \text{get-maximum-level } (\text{trail } y) \ (\text{remove1-mset } L \ D) \rangle$
 $\text{calculation}(1) \ i\text{-le-bt-y } \text{levL}$ **by** *linarith*
ultimately show *False* **using** $\text{backtrack.hyps}(4)$ **by** *linarith*
qed
then have $LL': L = L'$
using $LD \ LD' \ \text{remove1-mset-eq-remove1-mset-same}$ **unfolding** $DLD'[symmetric]$ **by** *fast*

have $[\text{simp}]: \text{atm-of } K \notin \text{atm-of } \text{'lits-of-l } M2$ **and**
 $[\text{simp}]: \text{atm-of } K \notin \text{atm-of } \text{'lits-of-l } M3$
using lev **unfolding** $M3 \ \text{cdcl}_W\text{-M-level-inv-def}$ **by** $(\text{auto simp: atm-lit-of-set-lits-of-l})$
{ assume $D: \text{remove1-mset } L \ D' = \{\#\}$
then have $j0: j = 0$ **using** $\text{levD } j$ **by** $(\text{simp add: } LL')$
have $\forall m \in \text{set } M1. \neg \text{is-decided } m$
using lev-K **unfolding** $j0 \ M3$ **by** $(\text{auto simp: atm-lit-of-set-lits-of-l image-Un} \ \text{filter-empty-conv})$
then have *False* **using** d **by** *auto*
}
moreover {
assume $D[\text{simp}]: \text{remove1-mset } L \ D' \neq \{\#\}$
have $i \leq j$
using lev count-H lev-K **unfolding** $M3 \ d \ \text{cdcl}_W\text{-M-level-inv-def}$ **by** $(\text{auto simp add:} \ \text{atm-lit-of-set-lits-of-l})$
have $j > 0$ **apply** (rule ccontr)
using $\langle i > 0 \rangle \ \text{lev-K}$ **unfolding** $M3 \ d$
by $(\text{auto simp add: rev-swap[symmetric] dest!: upt-decomp-lt})$
obtain L'' **where**
 $L'' \in \# \ \text{remove1-mset } L \ D'$ **and**


```

    L''D': get-level (trail y) L'' = get-maximum-level (trail y)
    (remove1-mset L D')
    using get-maximum-level-exists-lit-of-max-level[OF D, of trail y] by auto
  have L''M: atm-of L'' ∈ atm-of ' lits-of-l (trail y)
    using get-level-ge-0-atm-of-in[of 0 L'' trail y ] ⟨j>0⟩ levD L''D'
    i-le-bt-y levL by (simp add: LL' j)
  then have L'' ∈ lits-of-l (Decided Kh # d)
  proof -
    {
      assume L''H: atm-of L'' ∈ atm-of ' lits-of-l H
      then have atm-of L'' ∉ atm-of ' lits-of-l (c @ [Decided Kh])
        using n-d-y unfolding M by (auto simp: lits-of-def atm-of-eq-atm-of)
      then have get-level (trail y) L'' = get-level H L''
        using L''H unfolding M by auto
      moreover have get-level H L'' ≤ count-decided H
        by auto
      ultimately have False
        using ⟨j>0⟩ ⟨i ≤ j⟩ L''D' LL' ⟨get-level H L'' ≤ count-decided H⟩ count-H(1) j
        unfolding count-H by presburger
    }
    moreover
      have atm-of L'' ∈ atm-of ' lits-of-l H
        using DD' DH ⟨L'' ∈ # remove1-mset L D'⟩ atm-of-lit-in-atms-of LL' LD
        LD' by fastforce
      ultimately show ?thesis
        using DD' DH ⟨L'' ∈ # remove1-mset L D'⟩ atm-of-lit-in-atms-of
        by auto
    qed
  moreover
    have atm-of L'' ∈ atms-of (remove1-mset L D')
      using ⟨L'' ∈ # remove1-mset L D'⟩ by (auto simp: atms-of-def)

    then have atm-of L'' ∈ atm-of ' lits-of-l H
      using DH unfolding DD' unfolding LL' by blast
    ultimately have False
      using n-d-y unfolding M3 d LL' by (auto simp: lits-of-def)
  }
  ultimately show False by blast
qed
qed auto

```

lemma *cdcl_W-stgy-with-trail-end-has-not-been-learned:*

```

  assumes
    cdclW-stgy y z and
    cdclW-M-level-inv y and
    trail y = c @ Decided Kh # H and
    D ∉ # learned-clss y and
    LD: L ∈ # D and
    DH: atms-of (remove1-mset L D) ⊆ atm-of ' lits-of-l H and
    LH: atm-of L ∉ atm-of ' lits-of-l H and
    ∀ T. conflicting y = Some T ⟶ trail y ⊨as CNot T and
    trail z = c' @ Decided Kh # H
  shows D ∉ # learned-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** *LD = this(7)* **and** *DH = this(8)* **and** *LH = this(9)* **and** *confl = this(10)* **and**
trU = this(11)
obtain *c'* **where** *c': trail T = c' @ Decided Kh # H*
using *cp beginning-not-decided-invert[of - trail T c' Kh H]*
rtrancpl-cdcl_W-cp-dropWhile-trail[of T U] **unfolding** *trU full-def* **by** *fastforce*
show *?case*
using *cdcl_W-o-cannot-learn[OF o lev trY notin LD DH LH confl c']*
rtrancpl-cdcl_W-cp-learned-clause-inv cp **unfolding** *full-def* **by** *auto*
qed

lemma *rtrancpl-cdcl_W-stgy-with-trail-end-has-not-been-learned:*

assumes
*(λ a b. cdcl_W-stgy a b ∧ (∃ c. trail a = c @ Decided K # H @ []))** S z* **and**
cdcl_W-all-struct-inv S **and**
trail S = c @ Decided K # H **and**
D ∉ # learned-clss S **and**
LD: L ∈ # D **and**
DH: atm-of (remove1-mset L D) ⊆ atm-of ' lits-of-l H **and**
LH: atm-of L ∉ atm-of ' lits-of-l H **and**
∃ c'. trail z = c' @ Decided K # H
shows *D ∉ # learned-clss z*
using *assms(1-4,8)*
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-S = this(6)* **and** *trU = this(7)*
obtain *c* **where** *c: trail T = c @ Decided K # H* **using** *s* **by** *auto*
obtain *c'* **where** *c': trail U = c' @ Decided K # H* **using** *trU* **by** *blast*
have *cdcl_W** S T*
proof –
have $\forall p \text{ pa. } \exists s \text{ sa. } \forall sb \text{ sc sd se. } (\neg p^{**} (sb::'st) \text{ sc} \vee p \text{ s sa} \vee pa^{**} sb \text{ sc})$
 $\wedge (\neg pa \text{ s sa} \vee \neg p^{**} sd \text{ se} \vee pa^{**} sd \text{ se})$
by (*metis (no-types) mono-rtrancpl*)
then have *cdcl_W-stgy** S T*
using *st* **by** *blast*
then show *?thesis*
using *rtrancpl-cdcl_W-stgy-rtrancpl-cdcl_W* **by** *blast*
qed
then have *lev': cdcl_W-all-struct-inv T*
using *rtrancpl-cdcl_W-all-struct-inv-inv[of S T]* *lev* **by** *auto*
then have *confl': ∀ Ta. conflicting T = Some Ta ⟶ trail T ⊨_{as} CNot Ta*
unfolding *cdcl_W-all-struct-inv-def cdcl_W-conflicting-def* **by** *blast*
show *?case*
apply (*rule cdcl_W-stgy-with-trail-end-has-not-been-learned[OF - - c - LD DH LH confl' c']*)
using *s lev' IH c* **unfolding** *cdcl_W-all-struct-inv-def* **by** *blast+*
qed

lemma *cdcl_W-stgy-new-learned-clause:*

assumes *cdcl_W-stgy S T* **and**
lev: cdcl_W-M-level-inv S **and**

$E \notin \# \text{ learned-clss } S$ **and**
 $E \in \# \text{ learned-clss } T$
shows $\exists S'. \text{ backtrack } S S' \wedge \text{ conflicting } S = \text{Some } E \wedge \text{full cdcl}_W\text{-cp } S' T$
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** $o = \text{this}(1)$ **and** $cp = \text{this}(3)$ **and** $\text{not-yet} = \text{this}(5)$ **and** $\text{learned} = \text{this}(6)$
have $E \in \# \text{ learned-clss } T$
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

theorem 2.9.7 page 83 of Weidenbach's book

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
conf: conflicting S = Some E and
already-learned: E ∈ # clauses S and
R: trail R = []

shows *False*

proof –

have *M-lev: cdcl_W-M-level-inv R*
using *invR unfolding cdcl_W-all-struct-inv-def by auto*
have *cdcl_W-M-level-inv S*
using *M-lev assms(2) rtranclp-cdcl_W-stgy-consistent-inv by blast*
with *bt obtain L K :: 'v literal and M1 M2-loc :: ('v, 'v clause) ann-lits*
and *i :: nat where*
 $T: T \sim \text{cons-trail } (\text{Propagated } L E)$
 $(\text{reduce-trail-to } M1 (\text{add-learned-cls } E$
 $(\text{update-backtrack-lvl } i (\text{update-conflicting } \text{None } S))))$
and
 $\text{decomp}: (\text{Decided } K \# M1, M2\text{-loc}) \in$
 $\text{set } (\text{get-all-ann-decomposition } (\text{trail } S))$ **and**
 $LD: L \in \# E$ **and**
 $k: \text{get-level } (\text{trail } S) L = \text{backtrack-lvl } S$ **and**
 $\text{level}: \text{get-level } (\text{trail } S) L = \text{get-maximum-level } (\text{trail } S) E$ **and**
 $\text{conf-S}: \text{conflicting } S = \text{Some } E$ **and**
 $i: i = \text{get-maximum-level } (\text{trail } S) (\text{remove1-mset } L E)$ **and**
 $\text{lev-K}: \text{get-level } (\text{trail } S) K = \text{Suc } i$
using *conf apply (induction rule: backtrack.induct)*
apply (*simp del: state-simp*)
by *blast*
obtain *M2 where*
 $M: \text{trail } S = M2 @ \text{Decided } K \# M1$
using *get-all-ann-decomposition-exists-prepend[OF decomp] unfolding i by (metis append-assoc)*
let *?E' = remove1-mset L E*
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 *conf: cdcl_W-conflicting S unfolding cdcl_W-all-struct-inv-def by blast*
then have *trail S ⊢_{as} CNot E unfolding cdcl_W-conflicting-def conf-S by auto*

```

then have MD: trail S  $\models_{as}$  CNot E by auto
then have MD': trail S  $\models_{as}$  CNot ?E' using true-annot-CNot-diff by blast
have lev': cdclW-M-level-inv S using invS unfolding cdclW-all-struct-inv-def by blast

have lev: cdclW-M-level-inv R using invR unfolding cdclW-all-struct-inv-def by blast
then have vars-of-D: atms-of ?E'  $\subseteq$  atm-of ' lits-of-l M1
  using backtrack-atms-of-D-in-M1[OF lev' - decomp - -, of E - i T] confl-S conf T decomp k
  level lev' lev-K unfolding i cdclW-conflicting-def by (auto simp: cdclW-M-level-inv-decomp)
have no-dup (trail S) using lev' by (auto simp: cdclW-M-level-inv-decomp)
have vars-in-M1:
   $\forall x \in \text{atms-of } ?E'. x \notin \text{atm-of ' lits-of-l } (M2 @ [\text{Decided } K])$ 
  unfolding Set.Ball-def apply (intro impI allI)
  apply (rule vars-of-D distinct-atms-of-incl-not-in-other[of
    M2 @ Decided K # [] M1 ?E'])
  using (no-dup (trail S)) M vars-of-D by simp-all
have M1-D: M1  $\models_{as}$  CNot ?E'
  using vars-in-M1 true-annots-remove-if-notin-vars[of M2 @ Decided K # [] M1 CNot ?E']
  MD' M by simp

have backtrack-lvl S > 0 using lev' unfolding cdclW-M-level-inv-def M by auto

obtain M1' K' Ls where
  M': trail S = Ls @ Decided K' # M1' and
  Ls:  $\forall l \in \text{set } Ls. \neg \text{is-decided } l$  and
  set M1  $\subseteq$  set M1'
proof -
  let ?Ls = takeWhile (Not o is-decided) (trail S)
  have MLs: trail S = ?Ls @ dropWhile (Not o is-decided) (trail S)
    by auto
  have dropWhile (Not o is-decided) (trail S)  $\neq$  [] unfolding M by auto
  moreover
    from hd-dropWhile[OF this] have is-decided(hd (dropWhile (Not o is-decided) (trail S)))
      by simp
  ultimately
    obtain K' where
      K'k: dropWhile (Not o is-decided) (trail S)
        = Decided K' # tl (dropWhile (Not o is-decided) (trail S))
      by (cases dropWhile (Not o is-decided) (trail S);
        cases hd (dropWhile (Not o is-decided) (trail S)))
        simp-all
  moreover have  $\forall l \in \text{set } ?Ls. \neg \text{is-decided } l$  using set-takeWhileD by force
  moreover have set M1  $\subseteq$  set (tl (dropWhile (Not o is-decided) (trail S)))
    unfolding M by (induction M2) auto
  ultimately show ?thesis using that[of takeWhile (Not o is-decided) (trail S)
    K' tl (dropWhile (Not o is-decided) (trail S))] MLs by simp
qed

have M1'-D: M1'  $\models_{as}$  CNot ?E' using M1-D (set M1  $\subseteq$  set M1') by (auto intro: true-annots-mono)
have -L  $\in$  lits-of-l (trail S) using conf confl-S LD unfolding cdclW-conflicting-def
  by (auto simp: in-CNot-implies-uminus)
have L-notin: atm-of L  $\in$  atm-of ' lits-of-l Ls  $\vee$  atm-of L = atm-of K'
proof (rule ccontr)
  assume  $\neg$  ?thesis
  then have atm-of L  $\notin$  atm-of ' lits-of-l (Decided K' # rev Ls) by simp
  then have get-level (trail S) L = get-level M1' L
    unfolding M' by auto

```

```

moreover
  have get-level  $M1' L \leq \text{count-decided } M1'$ 
    by auto
  then have get-level  $M1' L < \text{backtrack-lvl } S$ 
    using lev' unfolding cdclW-M-level-inv-def  $M'$ 
    by (auto simp del: count-decided-ge-get-level)
  ultimately show False using  $k$  by linarith
qed
obtain  $Y Z$  where
   $RY: \text{cdcl}_W\text{-stgy}^{**} R Y$  and
   $YZ: \text{cdcl}_W\text{-stgy } Y Z$  and
   $nt: \neg (\exists c. \text{trail } Y = c @ \text{Decided } K' \# M1' @ [])$  and
   $Z: (\lambda a b. \text{cdcl}_W\text{-stgy } a b \wedge (\exists c. \text{trail } a = c @ \text{Decided } K' \# M1' @ []))^{**} Z S$ 
  using rtrancpl-cdclW-new-decided-at-beginning-is-decide' [OF  $st' - - \text{lev}$ , of  $Ls K'$ 
     $M1' []$ ] unfolding  $R M'$  by auto
have [simp]: cdclW-M-level-inv  $Y$ 
  using  $RY$  lev rtrancpl-cdclW-stgy-consistent-inv by blast
obtain  $M'$  where  $trZ: \text{trail } Z = M' @ \text{Decided } K' \# M1'$ 
  using rtrancpl-cdclW-stgy-with-trail-end-has-trail-end [OF  $Z$ ]  $M'$  by auto
have no-dup (trail  $Y$ )
  using  $RY$  lev rtrancpl-cdclW-stgy-consistent-inv unfolding cdclW-M-level-inv-def by blast
then obtain  $Y'$  where
   $dec: \text{decide } Y Y'$  and
   $Y'Z: \text{full } \text{cdcl}_W\text{-cp } Y' Z$  and
  no-step cdclW-cp  $Y$ 
  using cdclW-stgy-trail-has-new-decided-is-decide-step [OF  $YZ nt Z$ ]  $M'$  by auto
have  $trY: \text{trail } Y = M1'$ 
proof –
  obtain  $M'$  where  $M: \text{trail } Z = M' @ \text{Decided } K' \# M1'$ 
    using rtrancpl-cdclW-stgy-with-trail-end-has-trail-end [OF  $Z$ ]  $M'$  by auto
  obtain  $M''$  where  $M'': \text{trail } Z = M'' @ \text{trail } Y'$  and  $\forall m \in \text{set } M''. \neg \text{is-decided } m$ 
    using  $Y'Z$  rtrancpl-cdclW-cp-dropWhile-trail' unfolding full-def by blast
  obtain  $M'''$  where  $\text{trail } Y' = M''' @ \text{Decided } K' \# M1'$ 
    using  $M''$  unfolding  $M$ 
    by (metis (no-types, lifting)  $\langle \forall m \in \text{set } M''. \neg \text{is-decided } m \rangle$  beginning-not-decided-invert)
  then show ?thesis using  $dec nt$  by (induction  $M'''$ ) (auto elim: decideE)
qed
have  $Y\text{-CT}: \text{conflicting } Y = \text{None}$  using  $\langle \text{decide } Y Y' \rangle$  by (auto elim: decideE)
have cdclW**  $R Y$  by (simp add: RY rtrancpl-cdclW-stgy-rtrancpl-cdclW)
then have init-clss  $Y = \text{init-clss } R$  using rtrancpl-cdclW-init-clss [of  $R Y$ ]  $M\text{-lev}$  by auto
{ assume  $DL: E \in \# \text{clauses } Y$ 
  have atm-of  $L \notin \text{atm-of ' lits-of-l } M1$ 
    apply (rule backtrack-lit-skipped [of  $- S$ ])
    using decomp  $i k \text{lev' lev-K}$  unfolding cdclW-M-level-inv-def by auto
  then have  $LM1: \text{undefined-lit } M1 L$ 
    by (metis Decided-Propagated-in-iff-in-lits-of-l atm-of-uminus image-eqI)
  have  $L\text{-tr}Y: \text{undefined-lit } (\text{trail } Y) L$ 
    using  $L\text{-notin}$  (no-dup (trail  $S$ )) unfolding defined-lit-map  $trY M'$ 
    by (auto simp add: image-iff lits-of-def)
  have  $Ex$  (propagate  $Y$ )
    using propagate-rule [of  $Y E L$ ]  $DL M1'\text{-D}$   $L\text{-tr}Y$   $Y\text{-CT}$   $trY LD$  by auto
  then have False using  $\langle \text{no-step } \text{cdcl}_W\text{-cp } Y \rangle$  propagate' by blast
}
moreover {
  assume  $DL: E \notin \# \text{clauses } Y$ 
  have  $lY\text{-l}Z: \text{learned-clss } Y = \text{learned-clss } Z$ 

```

```

    using dec Y'Z rtranclp-cdclW-cp-learned-clause-inv[of Y' Z] unfolding full-def
    by (auto elim: decideE)
  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 n: E ∉ # learned-clss Z
    using DL lY-lZ YZ unfolding clauses-def by auto
  have E ∉ # learned-clss S
    apply (rule rtranclp-cdclW-stgy-with-trail-end-has-not-been-learned[OF Z invZ trZ])
    apply (simp add: n)
    using LD apply simp
    apply (metis (no-types, lifting) ⟨set M1 ⊆ set M1⟩' image-mono order-trans
        vars-of-D lits-of-def)
    using L-notin ⟨no-dup (trail S)⟩ unfolding M' by (auto simp add: image-iff lits-of-def)
  then have False
    using already-learned DL confl st' M-lev rtranclp-cdclW-stgy-no-more-init-clss[of R S]
    unfolding M'
    by (simp add: ⟨init-clss Y = 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: rtranclp-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 rtranclp-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.induct) (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 elim: decideE skipE resolveE)
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 rtranclp-cdclW-stgy-distinct-mset-clauses[OF - st] assms
  by (auto simp: cdclW-all-struct-inv-def distinct-cdclW-state-def)

```

Decrease of a Measure

```

fun cdclW-measure where
  cdclW-measure S =
    [(3::nat) ^ (card (atms-of-mm (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-mm (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-mm (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 conflict-driven-clause-learningW
begin

```

```

lemma learned-clss-less-upper-bound:
  fixes S :: 'st
  assumes
    distinct-cdclW-state S and
    ∀ s ∈ # learned-clss S. ¬tautology s
  shows card(set-mset (learned-clss S)) ≤ 3 ^ card (atms-of-mm (learned-clss S))
proof -
  have set-mset (learned-clss S) ⊆ simple-clss (atms-of-mm (learned-clss S))
    apply (rule simplified-in-simple-clss)
    using assms unfolding distinct-cdclW-state-def by auto
  then have card(set-mset (learned-clss S))
    ≤ card (simple-clss (atms-of-mm (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 *cdcl_W-measure-decreasing*:
fixes $S :: 'st$
assumes
 cdcl_W S 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
 no-forget: *learned-clss S \subseteq # learned-clss S' and*
 no-relearn: $\bigwedge S'. \text{backtrack } S S' \implies \forall T. \text{conflicting } S = \text{Some } T \longrightarrow T \notin \# \text{learned-clss } S$
 and
 alien: *no-strange-atm S and*
 M-level: *cdcl_W-M-level-inv S and*
 no-taut: $\forall s \in \# \text{learned-clss } S. \neg \text{tautology } s$ **and**
 no-dup: *distinct-cdcl_W-state S and*
 confl: *cdcl_W-conflicting S*
shows $(\text{cdcl}_W\text{-measure } S', \text{cdcl}_W\text{-measure } S) \in \text{lexn less-than } 3$
using *assms(1) M-level assms(2,3)*
proof (*induct rule: cdcl_W-all-induct*)
case (*propagate C L*) **note** *conf = this(1) and undef = this(5) and T = this(6)*
have *propa:* *propagate S (cons-trail (Propagated L C) S)*
 using *propagate-rule[OF propagate.hyps(1,2)] propagate.hyps by auto*
then have *no-dup': no-dup (Propagated L C # trail S)*
 using *M-level cdcl_W-M-level-inv-decomp(2) undef defined-lit-map by auto*

let $?N = \text{init-clss } S$
have *no-strange-atm (cons-trail (Propagated L C) S)*
 using *alien cdcl_W.propagate cdcl_W-no-strange-atm-inv propa M-level by blast*
then have *atm-of ' lits-of-l (Propagated L C # trail S)*
 $\subseteq \text{atms-of-mm (init-clss } S)$
 using *undef unfolding no-strange-atm-def by auto*
then have *card (atm-of ' lits-of-l (Propagated L C # trail S))*
 $\leq \text{card (atms-of-mm (init-clss } S))$
 by (*meson atms-of-ms-finite card-mono finite-set-mset*)
then have *length (Propagated L C # trail S) \leq card (atms-of-mm ?N)*
 using *no-dup-length-eq-card-atm-of-lits-of-l no-dup' by fastforce*
then have *H:* *card (atms-of-mm (init-clss S)) - length (trail S)*
 $= \text{Suc (card (atms-of-mm (init-clss S)) - Suc (length (trail S)))}$
 by *simp*
show *?case using conf T undef by (auto simp: H lexn3-conv)*
next
case (*decide L*) **note** *conf = this(1) and undef = this(2) and T = this(4)*
moreover
 have *dec:* *decide S (cons-trail (Decided L) (incr-lvl S))*
 using *decide-rule decide.hyps by force*
 then have *cdcl_W:cdcl_W S (cons-trail (Decided L) (incr-lvl S))*
 using *cdcl_W.simps cdcl_W-o.intros by blast*
moreover
 have *lev:* *cdcl_W-M-level-inv (cons-trail (Decided L) (incr-lvl S))*
 using *cdcl_W M-level cdcl_W-consistent-inv[OF cdcl_W] by auto*
 then have *no-dup:* *no-dup (Decided L # trail S)*
 using *undef unfolding cdcl_W-M-level-inv-def by auto*
 have *no-strange-atm (cons-trail (Decided L) (incr-lvl S))*
 using *M-level alien calculation(4) cdcl_W-no-strange-atm-inv by blast*
 then have *length (Decided L # (trail S))*
 $\leq \text{card (atms-of-mm (init-clss } S))$


```

    using no-dup undef
    length-model-le-vars[of cons-trail (Decided L) (incr-lvl S)]
    by fastforce
ultimately show ?case using conf by (simp add: le3-conv)
next
case (skip L C' M D) note tr = this(1) and conf = this(2) and T = this(5)
show ?case using conf T by (simp add: tr le3-conv)
next
case conflict
then show ?case by (simp add: le3-conv)
next
case resolve
then show ?case using finite by (simp add: le3-conv)
next
case (backtrack L D K i M1 M2 T) note conf = this(1) and decomp = this(3) and T = this(8) and
lev = this(9)
have bt: backtrack S T
  using backtrack-rule[OF backtrack.hyps] by auto
have D ∉ # learned-clss S
  using no-relearn conf bt by auto
then have card-T:
  card (set-mset ({#D#} + learned-clss S)) = Suc (card (set-mset (learned-clss S)))
  by simp
have distinct-cdclW-state T
  using bt M-level distinct-cdclW-state-inv no-dup other cdclW-o.intros cdclW-bj.intros by blast
moreover have ∀ s ∈ # learned-clss T. ¬ 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-mm (learned-clss T))
  by (auto simp: learned-clss-less-upper-bound)
then have H: card (set-mset ({#D#} + learned-clss S))
  ≤ 3 ^ card (atms-of-mm ({#D#} + learned-clss S))
  using T decomp M-level by (simp add: cdclW-M-level-inv-decomp)
moreover
have atms-of-mm ({#D#} + learned-clss S) ⊆ atms-of-mm (init-clss S)
  using alien conf unfolding no-strange-atm-def by auto
then have card-f: card (atms-of-mm ({#D#} + learned-clss S))
  ≤ card (atms-of-mm (init-clss S))
  by (meson atms-of-mm-finite card-mono finite-set-mset)
then have (3::nat) ^ card (atms-of-mm ({#D#} + learned-clss S))
  ≤ 3 ^ card (atms-of-mm (init-clss S)) by simp
ultimately have (3::nat) ^ card (atms-of-mm (init-clss S))
  ≥ card (set-mset ({#D#} + learned-clss S))
  using le-trans by blast
then show ?case using decomp diff-less-mono2 card-T T M-level
  by (auto simp: cdclW-M-level-inv-decomp le3-conv)
next
case restart
then show ?case using alien by (auto simp: state-eq-def simp del: state-simp)
next
case (forget C T) note no-forget = this(9)
then have C ∈ # learned-clss S and C ∉ # learned-clss T
  using forget.hyps by auto
then have ¬ learned-clss S ⊆ # learned-clss T
  by (auto simp add: mset-leD)
then show ?case using no-forget by blast

```

qed

```

lemma propagate-measure-decreasing:
  fixes S :: 'st
  assumes propagate S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn less-than 3
  apply (rule cdclW-measure-decreasing)
  using assms(1) propagate apply blast
    using assms(1) apply (auto simp add: propagate.simps)[3]
    using assms(2) apply (auto simp add: cdclW-all-struct-inv-def)
  done

```

```

lemma conflict-measure-decreasing:
  fixes S :: 'st
  assumes conflict S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn less-than 3
  apply (rule cdclW-measure-decreasing)
  using assms(1) conflict apply blast
    using assms(1) apply (auto simp: state-eq-def simp del: state-simp elim!: conflictE)[3]
    using assms(2) apply (auto simp add: cdclW-all-struct-inv-def elim: conflictE)
  done

```

```

lemma decide-measure-decreasing:
  fixes S :: 'st
  assumes decide S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn less-than 3
  apply (rule cdclW-measure-decreasing)
  using assms(1) decide other apply blast
    using assms(1) apply (auto simp: state-eq-def simp del: state-simp elim!: decideE)[3]
    using assms(2) apply (auto simp add: cdclW-all-struct-inv-def elim: decideE)
  done

```

```

lemma cdclW-cp-measure-decreasing:
  fixes S :: 'st
  assumes cdclW-cp S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn less-than 3
  using assms
proof induction
  case conflict'
  then show ?case using conflict-measure-decreasing by blast
next
  case propagate'
  then show ?case using propagate-measure-decreasing by blast
qed

```

```

lemma tranclp-cdclW-cp-measure-decreasing:
  fixes S :: 'st
  assumes cdclW-cp++ S S' and cdclW-all-struct-inv S
  shows (cdclW-measure S', cdclW-measure S) ∈ lexn less-than 3
  using assms
proof induction
  case base
  then show ?case using cdclW-cp-measure-decreasing by blast
next
  case (step T U) note st = this(1) and step = this(2) and IH = this(3) and inv = this(4)
  then have (cdclW-measure T, cdclW-measure S) ∈ lexn less-than 3 by blast

```

moreover have $(cdcl_W\text{-measure } U, cdcl_W\text{-measure } T) \in \text{lexn less-than } 3$
using $cdcl_W\text{-cp-measure-decreasing}[OF \text{ step}] \text{ rtranclp-cdcl}_W\text{-all-struct-inv-inv inv}$
 $\text{trancplp-cdcl}_W\text{-cp-trancplp-cdcl}_W[OF \text{ st}]$
unfolding $\text{trans-def rtranclp-unfold}$
by blast
ultimately show $?case \text{ using } \text{lexn-transI}[OF \text{ trans-less-than}] \text{ unfolding } \text{trans-def} \text{ by } \text{blast}$
qed

lemma $cdcl_W\text{-stgy-step-decreasing}$:
fixes $R \ S \ T :: 'st$
assumes $cdcl_W\text{-stgy } S \ T$ **and**
 $cdcl_W\text{-stgy}^{**} \ R \ S$
 $\text{trail } R = []$ **and**
 $cdcl_W\text{-all-struct-inv } R$
shows $(cdcl_W\text{-measure } T, cdcl_W\text{-measure } S) \in \text{lexn less-than } 3$

proof –
have $cdcl_W\text{-all-struct-inv } S$
using assms
by $(\text{metis rtranclp-unfold rtranclp-cdcl}_W\text{-all-struct-inv-inv trancplp-cdcl}_W\text{-stgy-trancplp-cdcl}_W)$
with assms **show** $?thesis$
proof induction
case $(\text{conflict}' \ V)$ **note** $cp = \text{this}(1)$ **and** $inv = \text{this}(5)$
show $?case$
using $\text{trancplp-cdcl}_W\text{-cp-measure-decreasing}[OF \text{ HOL.conjunct1}[OF \text{ cp}[unfolding full1-def]] \text{ inv}]$
.

next
case $(\text{other}' \ T \ U)$ **note** $st = \text{this}(1)$ **and** $H = \text{this}(4,5,6,7)$ **and** $cp = \text{this}(3)$
have $cdcl_W\text{-all-struct-inv } T$
using $cdcl_W\text{-all-struct-inv-inv other other'}.hyps(1) \text{ other'}.prems(4)$ **by** blast
from $\text{trancplp-cdcl}_W\text{-cp-measure-decreasing}[OF - \text{this}]$
have $\text{le-or-eq}: (cdcl_W\text{-measure } U, cdcl_W\text{-measure } T) \in \text{lexn less-than } 3 \vee$
 $cdcl_W\text{-measure } U = cdcl_W\text{-measure } T$
using cp **unfolding** $\text{full-def rtranclp-unfold}$ **by** blast
moreover
have $cdcl_W\text{-M-level-inv } S$
using $cdcl_W\text{-all-struct-inv-def other'}.prems(4)$ **by** blast
with st **have** $(cdcl_W\text{-measure } T, cdcl_W\text{-measure } S) \in \text{lexn less-than } 3$
proof $(\text{induction rule:} \text{cdcl}_W\text{-o-induct})$
case $(\text{decide } T)$
then show $?case \text{ using } \text{decide-measure-decreasing } H \text{ decide.intros}[OF \text{ decide.hyps}] \text{ by } \text{blast}$
next
case $(\text{backtrack } L \ D \ K \ i \ M1 \ M2 \ T)$ **note** $\text{conf} = \text{this}(1)$ **and** $\text{decomp} = \text{this}(3)$ **and**
 $\text{undef} = \text{this}(8)$ **and** $T = \text{this}(9)$
have $bt: \text{backtrack } S \ T$
apply $(\text{rule backtrack-rule})$
using backtrack.hyps **by** auto
then have $\text{no-relearn}: \forall T. \text{conflicting } S = \text{Some } T \longrightarrow T \notin \# \text{learned-clss } S$
using $cdcl_W\text{-stgy-no-relearned-clause}[of \ R \ S \ T] \ H \ \text{conf}$
unfolding $cdcl_W\text{-all-struct-inv-def clauses-def}$ **by** auto
have $\text{inv}: cdcl_W\text{-all-struct-inv } S$
using $\langle cdcl_W\text{-all-struct-inv } S \rangle$ **by** blast
show $?case$
apply $(\text{rule } cdcl_W\text{-measure-decreasing})$
using $bt \ cdcl_W\text{-bj.backtrack } cdcl_W\text{-o.bj other}$ **apply** simp
using $bt \ T \ \text{undef} \ \text{decomp} \ \text{inv}$ **unfolding** $cdcl_W\text{-all-struct-inv-def}$

```

      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 (auto simp: leW3-conv)
  next
    case resolve
    then show ?case by (auto simp: leW3-conv)
  qed
ultimately show ?case
  by (metis (full-types) leW-transI transD trans-less-than)
qed
qed

```

Roughly corresponds to theorem 2.9.15 page 86 of Weidenbach's book (using a different bound)

```

lemma tranclp-cdclW-stgy-decreasing:
  fixes R S T :: 'st
  assumes cdclW-stgy++ R S
  trail R = [] and
  cdclW-all-struct-inv R
  shows (cdclW-measure S, cdclW-measure R) ∈ leW less-than 3
  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]
  leW-transI[OF trans-less-than, of 3] 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)) ∈ leW less-than 3
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 leW less-than 3 - - cdclW-measure])
  apply (simp add: wf wf-leW)
  using tranclp-cdclW-stgy-S0-decreasing by blast

```

```

lemma cdclW-cp-wf-all-inv:
  wf {(S', S). cdclW-all-struct-inv S ∧ cdclW-cp S S'}
  (is wf ?R)

```

```

proof (rule wf-bounded-measure[of -
  λS. card (atms-of-mm (init-cls S))+1
  λS. 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 cdclW-cp.simps cdclW-all-struct-inv-inv conflict cdclW.intros cdclW-all-struct-inv-inv
  by blast+
ultimately show ?case
  by (auto simp: cdclW-cp.simps state-eq-def simp del: state-simp elim!: conflictE propagateE
    dest: length-model-le-vars-all-inv)
qed

end

end

```

6.2 Merging backjump rules

```

theory CDCL-W-Merge
imports CDCL-W-Termination
begin

```

Before showing that Weidenbach's CDCL is included in NOT's CDCL, we need to work on a variant of Weidenbach's calculus: NOT's backjump assumes the existence of a clause that is suitable to backjump. This clause is obtained in W's CDCL by applying:

1. *conflict-driven-clause-learning_W.conflict* to find the conflict
2. the conflict is analysed by repetitive application of *conflict-driven-clause-learning_W.resolve* and *conflict-driven-clause-learning_W.skip*,
3. finally *conflict-driven-clause-learning_W.backtrack* is used to backtrack.

We show that this new calculus has the same final states than Weidenbach's CDCL if the calculus starts in a state such that the invariant holds and no conflict has been found yet. The latter condition holds for initial states.

6.2.1 Inclusion of the states

```

context conflict-driven-clause-learningW
begin
declare cdclW.intros[intro] cdclW-bj.intros[intro] cdclW-o.intros[intro]

lemma backtrack-no-cdclW-bj:
  assumes cdcl: cdclW-bj T U and inv: cdclW-M-level-inv V
  shows ¬backtrack V T
  using cdcl inv
  apply (induction rule: cdclW-bj.induct)
    apply (elim skipE, force elim!: backtrackE simp: cdclW-M-level-inv-def)
    apply (elim resolveE, force elim!: backtrackE simp: cdclW-M-level-inv-def)
  apply standard
  apply (elim backtrackE)
  apply (force simp del: state-simp simp add: state-eq-def cdclW-M-level-inv-decomp)

```

done

skip-or-resolve corresponds to the *analyze* function in the code of MiniSAT.

inductive *skip-or-resolve* :: '*st* ⇒ '*st* ⇒ bool **where**
s-or-r-skip[*intro*]: *skip S T* ⇒ *skip-or-resolve S T* |
s-or-r-resolve[*intro*]: *resolve S T* ⇒ *skip-or-resolve S T*

lemma *rtrancpl-cdcl_W-bj-skip-or-resolve-backtrack*:
assumes *cdcl_W-bj** S U* **and** *inv: cdcl_W-M-level-inv S*
shows *skip-or-resolve** S U* ∨ (∃ *T*. *skip-or-resolve** S T* ∧ *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*) *cdcl_W-bj⁺⁺ S U*

using *st unfolding rtrancpl-unfold by blast*

then show ?*case*

proof *cases*

case *SUp*

have $\bigwedge T. \text{skip-or-resolve}^{**} S T \Rightarrow \text{cdcl}_W^{**} S T$

using *mono-rtrancpl[of skip-or-resolve cdcl_W]*

by (*blast intro: skip-or-resolve.cases*)

then have *skip-or-resolve** S U*

using *bj IH inv backtrack-no-cdcl_W-bj rtrancpl-cdcl_W-consistent-inv[OF - inv]* **by** *meson*

then show ?*thesis*

using *bj by (auto simp: cdcl_W-bj.simps dest!: skip-or-resolve.intros)*

next

case *SU*

then show ?*thesis*

using *bj by (auto simp: cdcl_W-bj.simps dest!: skip-or-resolve.intros)*

qed

qed

lemma *rtrancpl-skip-or-resolve-rtrancpl-cdcl_W*:

*skip-or-resolve** S T* ⇒ *cdcl_W** S T*

by (*induction rule: rtrancpl-induct*)

(*auto dest!: cdcl_W-bj.intros cdcl_W.intros cdcl_W-o.intros simp: skip-or-resolve.simps*)

definition *backjump-l-cond* :: '*v* clause ⇒ '*v* clause ⇒ '*v* literal ⇒ '*st* ⇒ '*st* ⇒ bool **where**

backjump-l-cond ≡ λ*C C' L' S T*. *True*

definition *inv_{NOT}* :: '*st* ⇒ bool **where**

inv_{NOT} ≡ λ*S*. *no-dup (trail S)*

declare *inv_{NOT}-def[simp]*

end

context *conflict-driven-clause-learning_W*

begin

6.2.2 More lemmas conflict-propagate and backjumping

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-ann-decomposition-exists-prepend
elim!: backtrackE skipE resolveE
simp: cdcl_W-M-level-inv-def)+

lemma *wf-cdcl_W-bj*:
wf {(b,a). cdcl_W-bj a b ∧ 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** *simp*

lemma *cdcl_W-bj-exists-normal-form*:

assumes *lev: cdcl_W-M-level-inv S*
shows $\exists T. \text{full } cdcl_W\text{-bj } S \ T$

proof –

obtain *T* **where** *T: full (λa b. cdcl_W-bj a b ∧ 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]* **by** *blast*
then have *cdcl_W-M-level-inv T*
using *rtrancp-cdcl_W-consistent-inv lev* **by** *auto*

ultimately show *?thesis* **using** *T unfolding full-def* **by** *auto*

qed

lemma *rtrancp-skip-state-decomp*:

assumes *skip** S T* **and** *no-dup (trail S)*

shows

$\exists M. \text{trail } S = M @ \text{trail } T \wedge (\forall m \in \text{set } M. \neg \text{is-decided } m)$
init-clss S = init-clss T
learned-clss S = learned-clss T
backtrack-lvl S = backtrack-lvl T
conflicting S = conflicting T

using *assms* **by** (*induction rule: rtrancp-induct*)
(auto simp del: state-simp simp: state-eq-def elim!: skipE)

More backjumping

Backjumping after skipping or jump directly **lemma** *rtrancp-skip-backtrack-backtrack*:

assumes

*skip** S T* **and**

```

    backtrack T W and
    cdclW-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 cdclW-all-struct-inv V
    using rtrancp-mono[of skip cdclW] assms(3) rtrancp-cdclW-all-struct-inv-inv mono-rtrancp
    by (auto dest!: bj other cdclW-bj.skip)
  then have cdclW-M-level-inv V
    unfolding cdclW-all-struct-inv-def by auto
  then obtain K i M1 M2 L D where
    conf: conflicting V = Some D and
    LD: L ∈ # D and
    decomp: (Decided K # M1, M2) ∈ set (get-all-ann-decomposition (trail V)) and
    lev-L: get-level (trail V) L = backtrack-lvl V and
    max: get-level (trail V) L = get-maximum-level (trail V) D and
    max-D: get-maximum-level (trail V) (remove1-mset L D) ≡ i and
    lev-k: get-level (trail V) K = Suc i and
    W: W ∼ cons-trail (Propagated L D)
    (reduce-trail-to M1
    (add-learned-cls D
    (update-backtrack-lvl i
    (update-conflicting None V))))
  using bt inv by (elim backtrackE) metis+
  obtain L' C' M E where
    tr: trail T = Propagated L' C' # M and
    raw: conflicting T = Some E and
    LE: -L' ∉ # E and
    E: E ≠ {#} and
    V: V ∼ tl-trail T
    using skip by (elim skipE) metis
  let ?M = Propagated L' C' # trail V
  have tr-M: trail T = ?M
    using tr V by auto
  have MT: M = tl (trail T) and MV: M = trail V
    using tr V by auto
  have DE[simp]: D = E
    using V conf raw by (auto simp add: state-eq-def simp del: state-simp)
  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 tr-M unfolding cdclW-M-level-inv-def by auto
  let ?k = backtrack-lvl T
  have [simp]:
    backtrack-lvl V = ?k
    using V by simp
  have ?k > 0

```



```

    using decomp M-lev V tr unfolding cdclW-M-level-inv-def by auto
  then have atm-of L ∈ atm-of ' lits-of-l (trail V)
    using lev-L get-level-ge-0-atm-of-in[of 0 L trail V] by auto
  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-l (trail V)
    using n-d' unfolding lits-of-def by auto
  have ?M ⊨as CNot D
    using inv' raw unfolding cdclW-conflicting-def cdclW-all-struct-inv-def tr-M by auto
  then have L' ∉ # (remove1-mset L D)
    using L-L' L'-M ⟨Propagated L' C' # trail V ⊨as CNot D⟩
    unfolding true-annots-true-cls true-cls-def
    by (auto simp: uminus-lit-swap atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set dest!: in-diffD)
  have [simp]: trail (reduce-trail-to M1 T) = M1
    using decomp tr W V by auto
  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 = init-cls V and [simp]: learned-cls S = learned-cls V
    using rtrancp-skip-state-decomp[OF ⟨skip** S V⟩] V
    by (auto simp del: state-simp simp: state-eq-def)
  then have
    W-S: W ∼ cons-trail (Propagated L E) (reduce-trail-to M1
      (add-learned-cls E (update-backtrack-lvl i (update-conflicting None T))))
    using W V M-lev decomp tr
    by (auto simp del: state-simp simp: state-eq-def cdclW-M-level-inv-def)

  obtain M2' where
    decomp': (Decided K # M1, M2') ∈ set (get-all-ann-decomposition (trail T))
    using decomp V unfolding tr-M by (cases hd (get-all-ann-decomposition (trail V)),
      cases get-all-ann-decomposition (trail V)) auto
  moreover
    from L-L' have get-level ?M L = ?k
      using lev-L V by (auto split: if-split-asm)
  moreover
    have atm-of L' ∉ atms-of D
      by (metis DE LE L-L' ⟨L' ∉ # (remove1-mset L D)⟩ in-remove1-mset-neq
        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
      using calculation(2) lev-L max by auto
  moreover
    have atm-of L' ∉ atms-of ((remove1-mset L D))
      by (metis DE LE L-L' ⟨L' ∉ # (remove1-mset L D)⟩
        atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set atms-of-def in-remove1-mset-neq
        in-atms-of-remove1-mset-in-atms-of)
    have i = get-maximum-level ?M ((remove1-mset L D))
      using max-D ⟨atm-of L' ∉ atms-of ((remove1-mset L D))⟩ by auto
  moreover have atm-of L' ≠ atm-of K
    using inv' get-all-ann-decomposition-exists-prepend[OF decomp]
    unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def tr MV by auto
  ultimately have backtrack T W
    apply -
    apply (rule backtrack-rule[of T - L K M1 M2' i W, OF raw])
    unfolding tr-M[symmetric]
    using LD apply simp

```

```

    apply simp
    apply simp
    apply simp
    apply auto[]
    using W-S lev-k tr MV apply auto[]
    using W-S lev-k apply auto[]
  done
then show ?thesis using IH inv by blast
qed

```

See also theorem *rtrancpl-skip-backtrack-backtrack*

lemma *rtrancpl-skip-backtrack-backtrack-end*:

```

assumes
  skip: skip** S T and
  bt: backtrack S W and
  inv: cdclW-all-struct-inv S
shows backtrack T W
using assms
proof -
  have M-lev: cdclW-M-level-inv S
    using bt inv unfolding cdclW-all-struct-inv-def by (auto elim!: backtrackE)
  then obtain K i M1 M2 L D where
    S: conflicting S = Some D and
    LD: L ∈ # D and
    decomp: (Decided K # M1, M2) ∈ set (get-all-ann-decomposition (trail S)) and
    lev-l: get-level (trail S) L = backtrack-lvl S and
    lev-l-D: get-level (trail S) L = get-maximum-level (trail S) D and
    i: get-maximum-level (trail S) (remove1-mset L D) ≡ i and
    lev-K: get-level (trail S) K = Suc i and
    W: W ~ cons-trail (Propagated L D)
      (reduce-trail-to M1
       (add-learned-cls D
        (update-backtrack-lvl i
         (update-conflicting None S))))
    using bt by (elim backtrackE)
    (simp-all add: cdclW-M-level-inv-decomp state-eq-def del: state-simp)
  let ?D = remove1-mset L D

  have [simp]: no-dup (trail S)
    using M-lev by (auto simp: cdclW-M-level-inv-decomp)
  have cdclW-all-struct-inv T
    using mono-rtrancpl[of skip cdclW] by (smt bj cdclW-bj.skip inv local.skip other
      rtrancpl-cdclW-all-struct-inv-inv)
  then have [simp]: no-dup (trail T)
    unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def by auto

  obtain MS MT where M: trail S = MS @ MT and MT: MT = trail T and nm: ∀ m ∈ set MS.
    ¬is-decided m
    using rtrancpl-skip-state-decomp(1)[OF skip] S M-lev by auto
  have T: state T = (MT, init-cls S, learned-cls S, backtrack-lvl S, Some D)
    using MT rtrancpl-skip-state-decomp[of S T] skip S
    by (auto simp del: state-simp simp: state-eq-def)

  have cdclW-all-struct-inv T
    apply (rule rtrancpl-cdclW-all-struct-inv-inv[OF - inv])
    using bj cdclW-bj.skip local.skip other rtrancpl-mono[of skip cdclW] by blast

```

then have $M_T \models_{as} CNot\ D$
 using $cdcl_W$ -all-struct-inv-def $cdcl_W$ -conflicting-def using T by blast
 then have $\forall L \in \#D. atm\text{-}of\ L \in atm\text{-}of\ 'lits\text{-}of\text{-}l\ M_T$
 by (meson atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set
 true-annots-true-cls-def-iff-negation-in-model)
 moreover have no-dup (trail S)
 using inv unfolding $cdcl_W$ -all-struct-inv-def $cdcl_W$ -M-level-inv-def by auto
 ultimately have $\forall L \in \#D. atm\text{-}of\ L \notin atm\text{-}of\ 'lits\text{-}of\text{-}l\ MS$
 unfolding M unfolding lits-of-def by auto
 then have $H: \bigwedge L. L \in \#D \implies get\text{-}level\ (trail\ S)\ L = get\text{-}level\ M_T\ L$
 unfolding M by (fastforce simp: lits-of-def)
 have [simp]: get-maximum-level (trail S) $D = get\text{-}maximum\text{-}level\ M_T\ D$
 using $\langle M_T \models_{as} CNot\ D \rangle M\ nm\ \langle \forall L \in \#D. atm\text{-}of\ L \notin atm\text{-}of\ 'lits\text{-}of\text{-}l\ MS \rangle$
 by (auto simp: get-maximum-level-skip-un-decided-not-present)

 have lev-l': get-level $M_T\ L = backtrack\text{-}lvl\ S$
 using lev-l LD by (auto simp: H)
 have [simp]: trail (reduce-trail-to $M1\ T$) = $M1$
 using T decomp $M\ nm$ by (smt M_T append-assoc beginning-not-decided-invert
 get-all-ann-decomposition-exists-prepend reduce-trail-to-trail-tl-trail-decomp)
 have $W: W \sim cons\text{-}trail\ (Propagated\ L\ D)\ (reduce\text{-}trail\text{-}to\ M1$
 (add-learned-cls $D\ (update\text{-}backtrack\text{-}lvl\ i\ (update\text{-}conflicting\ None\ T))))$
 using $W\ T\ i$ decomp by (auto simp del: state-simp simp: state-eq-def)
 have lev-l-D': get-level $M_T\ L = get\text{-}maximum\text{-}level\ M_T\ D$
 using lev-l-D LD by (auto simp: H)
 have [simp]: get-maximum-level (trail S) $?D = get\text{-}maximum\text{-}level\ M_T\ ?D$
 by (smt H get-maximum-level-exists-lit get-maximum-level-ge-get-level in-diffD le-antisym
 not-gr0 not-less)
 then have $i': i = get\text{-}maximum\text{-}level\ M_T\ ?D$
 using i by auto
 have Decided $K \# M1 \in set\ (map\ fst\ (get\text{-}all\text{-}ann\text{-}decomposition\ (trail\ S)))$
 using Set.imageI[OF decomp, of fst] by auto
 then have Decided $K \# M1 \in set\ (map\ fst\ (get\text{-}all\text{-}ann\text{-}decomposition\ M_T))$
 using fst-get-all-ann-decomposition-prepend-not-decided[OF nm] unfolding M by auto
 then obtain $M2'$ where decomp': (Decided $K \# M1, M2'$) $\in set\ (get\text{-}all\text{-}ann\text{-}decomposition\ M_T)$
 by auto
 moreover
 have atm-of $K \notin atm\text{-}of\ 'lits\text{-}of\text{-}l\ MS$
 using $\langle no\text{-}dup\ (trail\ S) \rangle decomp'$ unfolding $M\ M_T$
 by (auto simp: lits-of-def)
 then have get-level (trail T) $K = get\text{-}level\ (trail\ S)\ K$
 unfolding $M\ M_T$ by auto
 ultimately show backtrack $T\ W$
 apply –
 apply (rule backtrack.intros[of $T\ D$])
 using $T\ lev\text{-}l'\ lev\text{-}l\text{-}D'\ i'\ W\ LD\ lev\text{-}K\ i$ apply auto[7]
 using $T\ W$ unfolding i' [symmetric]
 by (auto simp del: state-simp simp: state-eq-def)
 qed

lemma $cdcl_W$ -bj-decomp-resolve-skip-and-bj:
 assumes $cdcl_W$ -bj** $S\ T$ and inv: $cdcl_W$ -M-level-inv S
 shows (skip-or-resolve** $S\ T$
 $\vee (\exists U. skip\text{-}or\text{-}resolve**\ S\ U \wedge backtrack\ U\ T))$
 using assms
proof induction

```

case base
then show ?case by simp
next
case (step T U) note st = this(1) and bj = this(2) and IH = this(3)
have IH: skip-or-resolve** S T
proof -
  { assume  $\exists U. \text{skip-or-resolve}^{**} S U \wedge \text{backtrack } U T$ 
    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 skip-or-resolve.simps)+
qed

```

lemma *resolve-skip-deterministic*:
 $\text{resolve } S T \implies \text{skip } S U \implies \text{False}$
 by (auto elim!: skipE resolveE)

lemma *list-same-level-decomp-is-same-decomp*:
 assumes $M\text{-}K: M = M1 @ \text{Decided } K \# M2$ and $M\text{-}K': M = M1' @ \text{Decided } K' \# M2'$ and
 $\text{lev}\text{-}KK': \text{get-level } M K = \text{get-level } M K'$ and
 $n\text{-}d: \text{no-dup } M$
 shows $K = K'$ and $M1 = M1'$ and $M2 = M2'$
 proof -
 {
 fix j j' K K' M1 M1' M2 M2'
 assume
 $M\text{-}K: M = M1 @ \text{Decided } K \# M2$ and
 $M\text{-}K': M = M1' @ \text{Decided } K' \# M2'$ and
 $\text{lev}\text{-}KK': \text{get-level } M K = \text{get-level } M K'$ and
 $j: M ! j = \text{Decided } K$ and $j\text{-}M: j < \text{length } M$ and
 $j': M ! j' = \text{Decided } K'$ and $j'\text{-}M: j' < \text{length } M$ and
 $jj: j' > j$
 have $j \geq \text{length } M1$
 proof (rule ccontr)
 assume $\neg \text{length } M1 \leq j$
 then have $j < \text{length } M1$
 by auto
 then have $\text{Decided } K \in \text{set } M1$
 using j unfolding M-K
 by (auto simp: nth-append in-set-conv-nth split: if-splits)
 from Set.imageI[OF this, of $\lambda L. \text{atm-of } (\text{lit-of } L)$]
 show False using n-d unfolding M-K by auto
 qed
 }

```

qed
moreover then have  $j' - \text{Suc}(\text{length } M1) < \text{length } M2$ 
  using  $j'-M$   $jj$   $M-K$  unfolding  $M-K'$  by (metis One-nat-def Suc-eq-plus1 add.left-commute
    le-less-trans length-append less-diff-conv2 list.size(4) not-less not-less-eq)
ultimately have  $\text{dec}: \text{Decided } K' \in \text{set } M2$ 
  using  $jj$   $j$   $j'$   $j'-M$  unfolding  $M-K$  by (auto simp: nth-append in-set-conv-nth List.nth-Cons')
obtain  $xs$   $ys$  where
   $M2: M2 = xs @ \text{Decided } K' \# ys$ 
  using List.split-list[OF dec] by auto
have [simp]:  $\text{atm-of } K \neq \text{atm-of } K'$ 
  using  $n-d$  unfolding  $M-K$   $M2$  by auto
have  $\text{atm-of } K \notin \text{atm-of ' lits-of-l } M1$  and  $\text{atm-of } K' \notin \text{atm-of ' lits-of-l } M1$  and
 $\text{atm-of } K' \notin \text{atm-of ' lits-of-l } xs$ 
  using  $n-d$  Set.imageI[OF dec, of  $\lambda L. \text{atm-of (lit-of } L)$ ] unfolding  $M-K$ 
  using  $n-d$  unfolding  $M-K$   $M2$ 
  by (auto simp: lits-of-def)
then have False
  using  $M2$  levKK' unfolding  $M-K$  by (auto simp: split: if-splits )
} note  $H = \text{this}$ 
have  $\text{Decided } K \in \text{set } M$  and  $\text{Decided } K' \in \text{set } M$ 
  using  $M-K$  apply simp
  using  $M-K'$  by simp
then obtain  $j$   $j'$  where
   $j: M ! j = \text{Decided } K$  and  $j-M: j < \text{length } M$  and
   $j': M ! j' = \text{Decided } K'$  and  $j'-M: j' < \text{length } M$ 
  using in-set-conv-nth by metis

have [simp]:  $j = j'$  using  $H$ [OF  $M-K$   $M-K' - j$   $j-M$   $j' j'-M$ ]
   $H$ [OF  $M-K'$   $M-K - j'$   $j'-M$   $j j-M$ ] levKK' by presburger
then show  $KK': K = K'$  using  $j$   $j'$  by auto

have  $j-M1: j = \text{length } M1$ 
proof (rule ccontr)
  assume  $j \neq \text{length } M1$ 
  moreover then have  $j - \text{Suc}(\text{length } M1) < \text{length } M2 \vee j < \text{length } M1$ 
    using  $j-M$   $M-K$  unfolding  $M-K'$  by force
  ultimately have  $\text{Decided } K \in \text{set } (M1 @ M2)$ 
    using  $j$  unfolding  $M-K$  by (auto simp: nth-append in-set-conv-nth split: if-splits)
  from Set.imageI[OF this, of  $\lambda L. \text{atm-of (lit-of } L)$ ]
  show False using  $n-d$  unfolding  $M-K$  by auto
qed
have  $j-M2: j' = \text{length } M1'$ 
proof (rule ccontr)
  assume  $j' \neq \text{length } M1'$ 
  moreover then have  $j' - \text{Suc}(\text{length } M1') < \text{length } M2' \vee j' < \text{length } M1'$ 
    using  $j'-M$   $M-K'$  unfolding  $M-K$  by force
  ultimately have  $\text{Decided } K' \in \text{set } (M1' @ M2')$ 
    using  $j'$  unfolding  $M-K'$  by (auto simp: nth-append in-set-conv-nth split: if-splits)
  from Set.imageI[OF this, of  $\lambda L. \text{atm-of (lit-of } L)$ ]
  show False using  $n-d$  unfolding  $M-K'$  by auto
qed

show  $M1 = M1' M2 = M2'$ 
  using arg-cong[OF  $M-K$ , of take  $j$ ]  $j-M1$  arg-cong[OF  $M-K'$ , of take  $j'$ ]  $j-M2$ 
  using arg-cong[OF  $M-K$ , of drop  $(j+1)$ ]  $j-M1$  arg-cong[OF  $M-K'$ , of drop  $(j'+1)$ ]  $j-M2$ 
  by auto

```

qed

lemma *backtrack-unique*:

assumes

bt-T: *backtrack S T* **and**

bt-U: *backtrack S U* **and**

inv: *cdcl_W-all-struct-inv S*

shows $T \sim U$

proof –

have *lev*: *cdcl_W-M-level-inv S*

using *inv* **unfolding** *cdcl_W-all-struct-inv-def* **by** *auto*

then obtain *K i M1 M2 L D* **where**

S: *conflicting S = Some D* **and**

LD: $L \in \# D$ **and**

decomp: $(Decided K \# M1, M2) \in set (get-all-ann-decomposition (trail S))$ **and**

lev-l: *get-level (trail S) L = backtrack-lvl S* **and**

lev-l-D: *get-level (trail S) L = get-maximum-level (trail S) D* **and**

i: *get-maximum-level (trail S) (remove1-mset L D) \equiv i* **and**

lev-K: *get-level (trail S) K = Suc i* **and**

T: $T \sim cons-trail (Propagated L D)$

$(reduce-trail-to M1$

$(add-learned-cls D$

$(update-backtrack-lvl i$

$(update-conflicting None S))))$

using *bt-T* **by** $(elim backtrackE) (force simp: cdcl_W-M-level-inv-def)+$

obtain *K' i' M1' M2' L' D'* **where**

S': *conflicting S = Some D'* **and**

LD': $L' \in \# D'$ **and**

decomp': $(Decided K' \# M1', M2') \in set (get-all-ann-decomposition (trail S))$ **and**

lev-l: *get-level (trail S) L' = backtrack-lvl S* **and**

lev-l-D: *get-level (trail S) L' = get-maximum-level (trail S) D'* **and**

i': *get-maximum-level (trail S) (remove1-mset L' D') \equiv i'* **and**

lev-K': *get-level (trail S) K' = Suc i'* **and**

U: $U \sim cons-trail (Propagated L' D')$

$(reduce-trail-to M1'$

$(add-learned-cls D'$

$(update-backtrack-lvl i'$

$(update-conflicting None S))))$

using *bt-U* *lev* **by** $(elim backtrackE) (force simp: cdcl_W-M-level-inv-def)+$

obtain *c* **where** *M*: *trail S = c @ M2 @ Decided K # M1*

using *decomp* **by** *auto*

obtain *c'* **where** *M'*: *trail S = c' @ M2' @ Decided K' # M1'*

using *decomp'* **by** *auto*

have *n-d*: *no-dup (trail S)* **and** *bt*: *backtrack-lvl S = count-decided (trail S)*

using *lev* **unfolding** *cdcl_W-M-level-inv-def* **by** *auto*

then have *atm-of K \notin atm-of ' lits-of-l (c @ M2)*

by $(auto simp: lits-of-def M)$

then have *i < backtrack-lvl S*

using *lev-K* **unfolding** *M bt* **by** $(auto simp add: image-Un)$

have $[simp]: L' = L$

proof $(rule ccontr)$

assume $\neg ?thesis$

then have $L' \in \# remove1-mset L D$

using *S S' LD LD'* **by** $(simp add: in-remove1-mset-neq)$

```

    then have get-maximum-level (trail S) (remove1-mset L D) ≥ backtrack-lvl S
      using ⟨get-level (trail S) L' = backtrack-lvl S⟩ get-maximum-level-ge-get-level
      by metis
    then show False using i' i ⟨i < backtrack-lvl S⟩ by auto
  qed
then have [simp]: D' = D
  using S S' by auto
have [simp]: i' = i
  using i i' by auto
have [simp]: K = K' and [simp]: M1 = M1'
  apply (rule list-same-level-decomp-is-same-decomp[of trail S c @ M2 K M1
    c' @ M2' K' M1'])
  using lev-K lev-K' M M' n-d apply (auto)[4]
  apply (rule list-same-level-decomp-is-same-decomp[of trail S c @ M2 K M1
    c' @ M2' K' M1'])
  using lev-K lev-K' M M' n-d apply (auto)[4]
done
show ?thesis using T U inv decomp by (auto simp del: state-simp simp: state-eq-def
  cdclW-all-struct-inv-def cdclW-M-level-inv-decomp)
qed

```

lemma *if-can-apply-backtrack-no-more-resolve:*

```

assumes
  skip: skip** S U and
  bt: backtrack S T and
  inv: cdclW-all-struct-inv S
shows ¬resolve U V
proof (rule ccontr)
  assume resolve: ¬¬resolve U V

```

obtain *L E D* **where**

```

  U: trail U ≠ [] and
  tr-U: hd-trail U = Propagated L E and
  LE: L ∈# E and
  confl-U: conflicting U = Some D and
  LD: -L ∈# D and
  get-maximum-level (trail U) ((remove1-mset (-L) D)) = backtrack-lvl U and
  V: V ∼ update-conflicting (Some (resolve-cls L D E)) (tl-trail U)
  using resolve by (auto elim!: resolveE)
have inv-U: cdclW-all-struct-inv U
  using mono-rtrancpl[of skip cdclW] by (meson bj cdclW-bj.skip inv local.skip other
    rtrancpl-cdclW-all-struct-inv-inv)
then have [iff]: no-dup (trail S) cdclW-M-level-inv S and [iff]: no-dup (trail U)
  using inv unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def by blast+
have inv-V: cdclW-all-struct-inv V
  using mono-rtrancpl[of resolve cdclW] inv-U resolve cdclW.simps cdclW-all-struct-inv-inv
  cdclW-bj.resolve cdclW-o.simps by blast
have
  S: init-clss U = init-clss S
  learned-clss U = learned-clss S
  backtrack-lvl U = backtrack-lvl S
  backtrack-lvl V = backtrack-lvl S
  conflicting S = Some D
  using rtrancpl-skip-state-decomp[OF skip] U confl-U V
  by (auto simp del: state-simp simp: state-eq-def)
obtain M0 where

```

tr-S: $\text{trail } S = M_0 @ \text{trail } U$ **and**
nm: $\forall m \in \text{set } M_0. \neg \text{is-decided } m$
using *rtrancp-skip-state-decomp*[*OF skip*] **by** *blast*

obtain $K' i' M1' M2' L' D'$ **where**
S': *conflicting* $S = \text{Some } D'$ **and**
LD': $L' \in \# D'$ **and**
decomp': $(\text{Decided } K' \# M1', M2') \in \text{set } (\text{get-all-ann-decomposition } (\text{trail } S))$ **and**
lev-l: $\text{get-level } (\text{trail } S) L' = \text{backtrack-lvl } S$ **and**
lev-l-D: $\text{get-level } (\text{trail } S) L' = \text{get-maximum-level } (\text{trail } S) D'$ **and**
i': $\text{get-maximum-level } (\text{trail } S) (\text{remove1-mset } L' D') \equiv i'$ **and**
lev-K': $\text{get-level } (\text{trail } S) K' = \text{Suc } i'$ **and**
R: $T \sim \text{cons-trail } (\text{Propagated } L' D')$
 $(\text{reduce-trail-to } M1'$
 $(\text{add-learned-cls } D'$
 $(\text{update-backtrack-lvl } i'$
 $(\text{update-conflicting } \text{None } S))))$

using *bt* **by** (elim backtrackE) *metis*

obtain c **where** $M: \text{trail } S = c @ M2' @ \text{Decided } K' \# M1'$
using *get-all-ann-decomposition-exists-prepend*[*OF decomp'*] **by** *auto*

have $i' < \text{backtrack-lvl } S$
using *count-decided-ge-get-level*[*of K' trail S*] *inv*
unfolding *cdcl_W-all-struct-inv-def cdcl_W-M-level-inv-def lev-K'*
by *linarith*

have $U: \text{trail } U = \text{Propagated } L E \# \text{trail } V$
using *tr-S U S V tr-U* $\langle \text{trail } U \neq [] \rangle$ **by** $(\text{cases trail } U) (\text{auto simp: lits-of-def})$

have $DD'[simp]: D' = D$
using $U S' S$ **by** *auto*

have $[simp]: L' = -L$
proof (rule ccontr)
assume $\neg ?thesis$
then have $-L \in \# \text{remove1-mset } L' D'$
using $DD' LD' LD$ **by** $(\text{simp add: in-remove1-mset-neq})$

moreover
have $M': \text{trail } S = M_0 @ \text{Propagated } L E \# \text{trail } V$
using *tr-S unfolding U* **by** *auto*
have *no-dup* $(\text{trail } S)$
using *inv U unfolding cdcl_W-all-struct-inv-def cdcl_W-M-level-inv-def* **by** *auto*

then have *atm-L-notin-M*: $\text{atm-of } L \notin \text{atm-of } ' (\text{lits-of-l } (\text{trail } V))$
using $M' U S$ **by** $(\text{auto simp: lits-of-def})$

have *get-lev-L*:
 $\text{get-level}(\text{Propagated } L E \# \text{trail } V) L = \text{backtrack-lvl } V$
using *inv-V unfolding cdcl_W-all-struct-inv-def cdcl_W-M-level-inv-def* **by** *auto*

have $\text{atm-of } L \notin \text{atm-of } ' (\text{lits-of-l } (\text{rev } M_0))$
using $\langle \text{no-dup } (\text{trail } S) \rangle M'$ **by** $(\text{auto simp: lits-of-def})$

then have $\text{get-level } (\text{trail } S) L = \text{backtrack-lvl } S$
using *get-lev-L S unfolding M'* **by** *auto*

ultimately
have $\text{get-maximum-level } (\text{trail } S) (\text{remove1-mset } L' D') \geq \text{backtrack-lvl } S$
by $(\text{metis get-maximum-level-ge-get-level get-level-uminus})$

then show *False*
using $\langle i' < \text{backtrack-lvl } S \rangle i'$ **by** *auto*

qed

have $\text{cdcl}_W^{**} S U$
using *bj cdcl_W-bj.skip local.skip mono-rtrancp*[*of skip cdcl_W S U*] **other** **by** *meson*

then have $cdcl_W\text{-all-struct-inv } U$
using $inv \text{ rtrancp-cdcl}_W\text{-all-struct-inv-inv}$ **by** $blast$
then have $Propagated \ L \ E \ \# \ trail \ V \models_{as} CNot \ D'$
using $U \text{ confl-}U$ **unfolding** $cdcl_W\text{-all-struct-inv-def}$ $cdcl_W\text{-conflicting-def}$ **by** $auto$
then have $\forall L' \in \# (remove1\text{-mset } L' \ D') .$
 $atm\text{-of } L' \in atm\text{-of } ' \text{ lits-of-l } (Propagated \ L \ E \ \# \ trail \ U)$
using $U \text{ atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set in-CNot-implies-uminus}(2)$
by $(fastforce \ dest: in\text{-diff}D)$
then have $\forall L' \in \# (remove1\text{-mset } L' \ D') .$
 $atm\text{-of } L' \notin atm\text{-of } ' \text{ lits-of-l } M_0$
using $\langle no\text{-dup } (trail \ S) \rangle$ **unfolding** $tr\text{-}S \ U$ **by** $(fastforce \ simp: lits\text{-of-def image-image})$
then have $get\text{-maximum-level } (trail \ S) (remove1\text{-mset } L' \ D') = backtrack\text{-lvl } S$
using $get\text{-maximum-level-skip-un-decided-not-present}[of \ remove1\text{-mset } L' \ D'$
 $M_0 \ trail \ U] \ tr\text{-}S \ nm \ U$
 $\langle get\text{-maximum-level } (trail \ U) ((remove1\text{-mset } (- \ L) \ D)) = backtrack\text{-lvl } U \rangle$
by $(auto \ simp: S)$
then show $False$
using $i' \ \langle i' < backtrack\text{-lvl } S \rangle$ **by** $auto$
qed

lemma $if\text{-can-apply-resolve-no-more-backtrack}$:

assumes
 $skip: skip^{**} \ S \ U$ **and**
 $resolve: resolve \ S \ T$ **and**
 $inv: cdcl_W\text{-all-struct-inv } S$
shows $\neg backtrack \ U \ V$
using $assms$
by $(meson \ if\text{-can-apply-backtrack-no-more-resolve} \ rtrancp.rtrancl\text{-refl}$
 $rtrancp\text{-skip-backtrack-backtrack})$

lemma $if\text{-can-apply-backtrack-skip-or-resolve-is-skip}$:

assumes
 $bt: backtrack \ S \ T$ **and**
 $skip: skip\text{-or-resolve}^{**} \ S \ U$ **and**
 $inv: cdcl_W\text{-all-struct-inv } S$
shows $skip^{**} \ S \ U$
using $assms(2,3,1)$
by $induction \ (simp\text{-all add: if\text{-can-apply-backtrack-no-more-resolve} \ skip\text{-or-resolve.simps})$

lemma $cdcl_W\text{-bj-bj-decomp}$:

assumes $cdcl_W\text{-bj}^{**} \ S \ W$ **and** $cdcl_W\text{-all-struct-inv } S$
shows
 $(\exists T \ U \ V. (\lambda S \ T. skip\text{-or-resolve } S \ T \wedge no\text{-step backtrack } S)^{**} \ S \ T$
 $\wedge (\lambda T \ U. resolve \ T \ U \wedge no\text{-step backtrack } T) \ T \ U$
 $\wedge skip^{**} \ U \ V \wedge backtrack \ V \ W)$
 $\vee (\exists T \ U. (\lambda S \ T. skip\text{-or-resolve } S \ T \wedge no\text{-step backtrack } S)^{**} \ S \ T$
 $\wedge (\lambda T \ U. resolve \ T \ U \wedge no\text{-step backtrack } T) \ T \ U \wedge skip^{**} \ U \ W)$
 $\vee (\exists T. skip^{**} \ S \ T \wedge backtrack \ T \ W)$
 $\vee skip^{**} \ S \ W \text{ (is } ?RB \ S \ W \vee ?R \ S \ W \vee ?SB \ S \ W \vee ?S \ S \ W)$

using $assms$

proof $induction$

case $base$

then show $?case$ **by** $simp$

next

case $(step \ W \ X)$ **note** $st = this(1)$ **and** $bj = this(2)$ **and** $IH = this(3)[OF \ this(4)]$ **and** $inv = this(4)$

```

have  $\neg ?RB\ S\ W$  and  $\neg ?SB\ S\ W$ 
proof (clarify, goal-cases)
  case (1 T U V)
  have skip-or-resolve** S T
    using 1(1) by (auto dest!: rtrancpl-and-rtrancpl-left)
  then show False
    by (metis (no-types, lifting) 1(2) 1(4) 1(5) backtrack-no-cdclW-bj
      cdclW-all-struct-inv-def cdclW-all-struct-inv-inv cdclW-o.bj local.bj other
      resolve rtrancpl-cdclW-all-struct-inv-inv rtrancpl-skip-backtrack-backtrack
      rtrancpl-skip-or-resolve-rtrancpl-cdclW step.premis)
  next
  case 2
  then show ?case by (meson assms(2) cdclW-all-struct-inv-def backtrack-no-cdclW-bj
    local.bj rtrancpl-skip-backtrack-backtrack)
qed
then have IH:  $?R\ S\ W \vee ?S\ S\ W$  using IH by blast

have cdclW** S W using mono-rtrancpl[of cdclW-bj cdclW] st by blast
then have inv-W: cdclW-all-struct-inv W by (simp add: rtrancpl-cdclW-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
    ( $\lambda S\ T.$  skip-or-resolve S T  $\wedge$  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 skip-or-resolve.cases)
then have cdclW-all-struct-inv U
  by (meson RS(2) cdclW-all-struct-inv-inv cdclW-bj.resolve cdclW-o.bj other
      rtrancpl-cdclW-all-struct-inv-inv step.prem)
{ fix U'
  assume skip** U U' and skip** U' W
  have cdclW-all-struct-inv U'
    using ⟨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 ∧ U'. skip** U' V ⇒ skip** U' W
        using skip by auto
      then have (λS T. skip-or-resolve S T ∧ no-step backtrack S)** U V
        using IH H by blast
      moreover have (λS T. skip-or-resolve S T ∧ no-step backtrack S)** V W
        by (simp add: local.skip r-into-rtrancpl st step.prem skip-or-resolve.intros)
      ultimately show ?case by simp
    qed
  then show ?thesis
    proof -
      have f1: ∀ p pa pb pc. ¬ p (pa) pb ∨ ¬ p** pb pc ∨ p** pa pc
        by (meson converse-rtrancpl-into-rtrancpl)
      have skip-or-resolve T U ∧ no-step backtrack T
        using RS(2) RS(3) by force
      then have (λp pa. skip-or-resolve p pa ∧ no-step backtrack p)** T W
        proof -
          have (∃ vr19 vr16 vr17 vr18. vr19 (vr16::'st) vr17 ∧ vr19** vr17 vr18
              ∧ ¬ vr19** vr16 vr18)
            ∨ ¬ (skip-or-resolve T U ∧ no-step backtrack T)
            ∨ ¬ (λuu uua. skip-or-resolve uu uua ∧ no-step backtrack uu)** U W
            ∨ (λuu uua. skip-or-resolve uu uua ∧ no-step backtrack uu)** T W
          by force
          then show ?thesis
            by (metis (no-types) ⟨(λS T. skip-or-resolve S T ∧ no-step backtrack S)** U W⟩
                ⟨skip-or-resolve T U ∧ no-step backtrack T⟩ f1)
        qed
      then have (λp pa. skip-or-resolve p pa ∧ 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) ⟨cdclW-all-struct-inv S⟩
        rtrancpl-cdclW-all-struct-inv-inv)
  then have no-step backtrack U'
    using if-can-apply-backtrack-no-more-resolve[OF ⟨skip** U' W⟩] res by blast
}
with S
have (λS T. skip-or-resolve S T ∧ 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 ∧ U'. skip** U' V ⇒ skip** U' W
      using skip by auto
    then have (λS T. skip-or-resolve S T ∧ no-step backtrack S)** S V
      using IH H by blast
    moreover have (λS T. skip-or-resolve S T ∧ no-step backtrack S)** V W
      by (simp add: local.skip r-into-rtrancpl st step.prem skip-or-resolve.intros)
    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 ~ V ∨ cdclW-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 ~ V
  | (bj-TV) cdclW-bj** T V
  using IH by blast
  then show ?case

```

```

proof cases
  case  $TV$ 
  have  $no\text{-}step\ cdcl_W\text{-}bj\ T$ 
    using  $\langle cdcl_W\text{-}M\text{-}level\text{-}inv\ T \rangle\ n\text{-}s\ cdcl_W\text{-}bj\text{-}state\text{-}eq\text{-}compatible[of\ T - V]\ TV$ 
    by  $(meson\ backtrack\text{-}state\text{-}eq\text{-}compatible\ cdcl_W\text{-}bj.simps\ resolve\text{-}state\text{-}eq\text{-}compatible\ skip\text{-}state\text{-}eq\text{-}compatible\ state\text{-}eq\text{-}ref)$ 
  then show  $?thesis$ 
    using  $s\text{-}o\text{-}r$  by  $auto$ 
next
  case  $bj\text{-}TV$ 
  then obtain  $U'$  where
     $T\text{-}U': cdcl_W\text{-}bj\ T\ U'$  and
     $cdcl_W\text{-}bj^{**}\ U'\ V$ 
    using  $IH\ n\text{-}s\ s\text{-}o\text{-}r$  by  $(metis\ rtranclp\text{-}unfold\ tranclpD)$ 
  have  $cdcl_W^{**}\ S\ T$ 
    by  $(metis\ (no\text{-}types,\ hide\text{-}lams)\ bj\ mono\text{-}rtranclp[of\ cdcl_W\text{-}bj\ cdcl_W]\ other\ st)$ 
  then have  $inv\text{-}T: cdcl_W\text{-}all\text{-}struct\text{-}inv\ T$ 
    by  $(metis\ (no\text{-}types,\ hide\text{-}lams)\ inv\ rtranclp\text{-}cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}inv)$ 

  have  $lev\text{-}U: cdcl_W\text{-}M\text{-}level\text{-}inv\ U$ 
    using  $s\text{-}o\text{-}r\ cdcl_W\text{-}consistent\text{-}inv\ lev\text{-}T\ other$  by  $blast$ 
  show  $?thesis$ 
    using  $s\text{-}o\text{-}r$ 
    proof cases
      case  $backtrack$ 
      then obtain  $V0$  where  $skip^{**}\ T\ V0$  and  $backtrack\ V0\ V$ 
        using  $IH\ if\text{-}can\text{-}apply\text{-}backtrack\text{-}skip\text{-}or\text{-}resolve\text{-}is\text{-}skip[OF\ backtrack - inv\text{-}T]$ 
         $cdcl_W\text{-}bj\text{-}decomp\text{-}resolve\text{-}skip\text{-}and\text{-}bj$ 
        by  $(meson\ bj\text{-}TV\ cdcl_W\text{-}bj.backtrack\ inv\text{-}T\ lev\text{-}T\ n\text{-}s\ rtranclp\text{-}skip\text{-}backtrack\text{-}backtrack\text{-}end)$ 
      then have  $cdcl_W\text{-}bj^{**}\ T\ V0$  and  $cdcl_W\text{-}bj\ V0\ V$ 
        using  $rtranclp\text{-}mono[of\ skip\ cdcl_W\text{-}bj]$  by  $blast+$ 
      then show  $?thesis$ 
        using  $\langle backtrack\ V0\ V \rangle\ \langle skip^{**}\ T\ V0 \rangle\ backtrack\text{-}unique\ inv\text{-}T\ local.backtrack\ rtranclp\text{-}skip\text{-}backtrack\text{-}backtrack$  by  $auto$ 
      next
      case  $resolve$ 
      then have  $U \sim U'$ 
        by  $(meson\ T\text{-}U'\ cdcl_W\text{-}bj.simps\ if\text{-}can\text{-}apply\text{-}backtrack\text{-}no\text{-}more\text{-}resolve\ inv\text{-}T\ resolve\text{-}skip\text{-}deterministic\ resolve\text{-}unique\ rtranclp.rtrancl\text{-}refl)$ 
      then show  $?thesis$ 
        using  $\langle cdcl_W\text{-}bj^{**}\ U'\ V \rangle\ unfolding\ rtranclp\text{-}unfold$ 
        by  $(meson\ T\text{-}U'\ bj\ cdcl_W\text{-}consistent\text{-}inv\ lev\text{-}T\ other\ state\text{-}eq\text{-}ref\ state\text{-}eq\text{-}sym\ tranclp\text{-}cdcl_W\text{-}bj\text{-}state\text{-}eq\text{-}compatible)$ 
      next
      case  $skip$ 
      consider
         $(sk)\ skip\ T\ U'$ 
         $| (bt)\ backtrack\ T\ U'$ 
        using  $T\text{-}U'$  by  $(meson\ cdcl_W\text{-}bj.cases\ local.skip\ resolve\text{-}skip\text{-}deterministic)$ 
      then show  $?thesis$ 
        proof cases
          case  $sk$ 
          then show  $?thesis$ 
            using  $\langle cdcl_W\text{-}bj^{**}\ U'\ V \rangle\ unfolding\ rtranclp\text{-}unfold$ 
            by  $(meson\ T\text{-}U'\ bj\ cdcl_W\text{-}all\text{-}inv(3)\ cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def\ inv\text{-}T\ local.skip\ other$ 

```

```

      tranclp-cdclW-bj-state-eq-compatible skip-unique state-eq-ref)
next
  case bt
  have skip++ T U
    using local.skip by blast
  have cdclW-bj U U'
    by (meson ⟨skip++ T U⟩ backtrack bt inv-T rtranclp-skip-backtrack-backtrack-end
      tranclp-into-rtranclp)
  then have cdclW-bj++ U V
    using ⟨cdclW-bj** U' V⟩ by auto
  then show ?thesis
    by (meson tranclp-into-rtranclp)
qed
qed
qed
qed

```

lemma *cdcl_W-bj-unique-normal-form*:

```

  assumes
    ST: cdclW-bj** S T and SU: cdclW-bj** S U and
    n-s-U: no-step cdclW-bj U and
    n-s-T: no-step cdclW-bj T and
    inv: cdclW-all-struct-inv S
  shows T ~ U
proof -
  have T ~ U ∨ cdclW-bj** T U
    using ST SU cdclW-bj-strongly-confluent inv n-s-U by blast
  then show ?thesis
    by (metis (no-types) n-s-T rtranclp-unfold state-eq-ref tranclp-unfold-begin)
qed

```

lemma *full-cdcl_W-bj-unique-normal-form*:

```

  assumes full cdclW-bj S T and full cdclW-bj S U and
    inv: cdclW-all-struct-inv S
  shows T ~ U
    using cdclW-bj-unique-normal-form assms unfolding full-def by blast

```

6.2.3 CDCL with Merging

inductive *cdcl_W-merge-restart* :: 'st ⇒ 'st ⇒ bool **where**

```

  fw-r-propagate: propagate S S' ⇒ cdclW-merge-restart S S' |
  fw-r-conflict: conflict S T ⇒ full cdclW-bj T U ⇒ cdclW-merge-restart S U |
  fw-r-decide: decide S S' ⇒ cdclW-merge-restart S S' |
  fw-r-rf: cdclW-rf S S' ⇒ cdclW-merge-restart S S'

```

lemma *rtranclp-cdcl_W-bj-rtranclp-cdcl_W*:

```

  cdclW-bj** S T ⇒ cdclW** S T
  using mono-rtranclp[of cdclW-bj cdclW] by blast

```

lemma *cdcl_W-merge-restart-cdcl_W*:

```

  assumes cdclW-merge-restart S T
  shows cdclW** S T
  using assms

```

proof *induction*

```

  case (fw-r-conflict S T U) note confl = this(1) and bj = this(2)

```

```

have cdclW S T using confl by (simp add: cdclW.intros r-into-rtrancp)
moreover
  have cdclW-bj** T U using bj unfolding full-def by auto
  then have cdclW** T U using rtrancp-cdclW-bj-rtrancp-cdclW by blast
ultimately show ?case by auto
qed (simp-all add: cdclW-o.intros cdclW.intros r-into-rtrancp)

lemma cdclW-merge-restart-conflicting-true-or-no-step:
  assumes cdclW-merge-restart S T
  shows conflicting T = None  $\vee$  no-step cdclW T
  using assms
proof induction
  case (fw-r-conflict S T U) note confl = this(1) and n-s = this(2)
  { fix D V
    assume cdclW U V and conflicting U = Some D
    then have False
      using n-s unfolding full-def
      by (induction rule: cdclW-all-rules-induct)
        (auto dest!: cdclW-bj.intros elim: decideE propagateE conflictE forgetE restartE)
  }
  then show ?case by (cases conflicting U) fastforce+
qed (auto simp add: cdclW-rf.simps elim: propagateE decideE restartE forgetE)

inductive cdclW-merge :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool where
  fw-propagate: propagate S S'  $\Longrightarrow$  cdclW-merge S S' |
  fw-conflict: conflict S T  $\Longrightarrow$  full cdclW-bj T U  $\Longrightarrow$  cdclW-merge S U |
  fw-decide: decide S S'  $\Longrightarrow$  cdclW-merge S S' |
  fw-forget: forget S S'  $\Longrightarrow$  cdclW-merge S S'

lemma cdclW-merge-cdclW-merge-restart:
  cdclW-merge S T  $\Longrightarrow$  cdclW-merge-restart S T
  by (meson cdclW-merge.cases cdclW-merge-restart.simps forget)

lemma rtrancp-cdclW-merge-trancp-cdclW-merge-restart:
  cdclW-merge** S T  $\Longrightarrow$  cdclW-merge-restart** S T
  using rtrancp-mono[of cdclW-merge cdclW-merge-restart] cdclW-merge-cdclW-merge-restart by blast

lemma cdclW-merge-rtrancp-cdclW:
  cdclW-merge S T  $\Longrightarrow$  cdclW** S T
  using cdclW-merge-cdclW-merge-restart cdclW-merge-restart-cdclW by blast

lemma rtrancp-cdclW-merge-rtrancp-cdclW:
  cdclW-merge** S T  $\Longrightarrow$  cdclW** S T
  using rtrancp-mono[of cdclW-merge cdclW**] cdclW-merge-rtrancp-cdclW by auto

lemmas rulesE =
  skipE resolveE backtrackE propagateE conflictE decideE restartE forgetE

lemma cdclW-all-struct-inv-trancp-cdclW-merge-trancp-cdclW-merge-cdclW-all-struct-inv:
  assumes
    inv: cdclW-all-struct-inv b
    cdclW-merge++ b a
  shows ( $\lambda S T. cdclW-all-struct-inv S \wedge cdclW-merge S T$ )++ 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 backtrack-is-full1-cdclW-bj:
  assumes bt: backtrack S T and inv: cdclW-M-level-inv S
  shows full1 cdclW-bj S T
  using bt inv backtrack-no-cdclW-bj unfolding full1-def by blast

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
  confl[simp] = this(5) and inv = this(4)
from cdclW
show ?case
proof (cases)
case propagate
moreover then have conflicting U = None and conflicting V = None
  by (auto elim: propagateE)
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 and conflicting V ≠ None
  by (auto elim!: conflictE simp del: state-simp simp: state-eq-def)
ultimately show ?thesis using IH by auto
next
case other
then show ?thesis
proof cases
case decide
then show ?thesis using IH cdclW-merge-restart.fw-r-decide[of U V] by (auto elim: decideE)
next
case bj
moreover {
  assume skip-or-resolve U V
  have f1: cdclW-bj++ U V
    by (simp add: local.bj tranclp.r-into-trancl)
  obtain T T' :: 'st where
    f2: cdclW-merge-restart** S U
      ∨ cdclW-merge-restart** S T ∧ conflicting U ≠ None
      ∧ conflict T T' ∧ cdclW-bj** T' U
    using IH confl by blast

```



```

    have conflicting V ≠ None ∧ conflicting U ≠ None
      using ⟨skip-or-resolve U V⟩
    by (auto simp: skip-or-resolve.simps state-eq-def elim!: skipE resolveE
        simp del: state-simp)
  then have ?thesis
    by (metis (full-types) IH f1 rtranclp-trans tranclp-into-rtranclp)
}
moreover {
  assume backtrack U V
  then have conflicting U ≠ None by (auto elim: backtrackE)
  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: backtrackE
        simp: cdclW-M-level-inv-decomp)
  have full cdclW-bj T' V
    apply (rule rtranclp-fullI[of cdclW-bj T' U V])
    using ⟨cdclW-bj** T' U⟩ apply fast
    using ⟨backtrack U V⟩ backtrack-is-full1-cdclW-bj invU unfolding full1-def full-def
    by blast
  then have ?thesis
    using cdclW-merge-restart.fw-r-conflict[of T T' V] ⟨conflict T T'⟩
    ⟨cdclW-merge-restart** S T⟩ ⟨conflicting V = 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 elim: restartE forgetE)
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 ⇒ 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 asms(2) cdclW-consistent-inv by blast
  }

```

```

    then obtain  $S''$  where  $\text{full } \text{cdcl}_W\text{-bj } S' S''$ 
    using  $\text{cdcl}_W\text{-bj-exists-normal-form[of } S']$  by auto
    then have  $\text{False}$ 
    using  $\langle \text{conflict } S S' \rangle \text{ assms}(3) \text{ fw-r-conflict}$  by blast
  }
  then show ?thesis
  using assms unfolding  $\text{cdcl}_W.\text{simps}$   $\text{cdcl}_W\text{-merge-restart.simps}$   $\text{cdcl}_W\text{-o.simps}$   $\text{cdcl}_W\text{-bj.simps}$ 
  by (auto elim: skipE resolveE backtrackE conflictE decideE restartE)
qed

```

```

lemma  $\text{cdcl}_W\text{-merge-restart-no-step-cdcl}_W\text{-bj}$ :
  assumes
     $\text{cdcl}_W\text{-merge-restart } S T$ 
  shows  $\text{no-step } \text{cdcl}_W\text{-bj } T$ 
  using assms
  by (induction rule:  $\text{cdcl}_W\text{-merge-restart.induct}$ )
  (force simp:  $\text{cdcl}_W\text{-bj.simps}$   $\text{cdcl}_W\text{-rf.simps}$   $\text{cdcl}_W\text{-merge-restart.simps}$   $\text{full-def}$ 
    elim!: rulesE)+

```

```

lemma  $\text{rtrancpl-cdcl}_W\text{-merge-restart-no-step-cdcl}_W\text{-bj}$ :
  assumes
     $\text{cdcl}_W\text{-merge-restart}^{**} S T$  and
     $\text{conflicting } S = \text{None}$ 
  shows  $\text{no-step } \text{cdcl}_W\text{-bj } T$ 
  using assms unfolding  $\text{rtrancpl-unfold}$ 
  apply (elim disjE)
  apply (force simp:  $\text{cdcl}_W\text{-bj.simps}$   $\text{cdcl}_W\text{-rf.simps}$  elim!: rulesE)
  by (auto simp:  $\text{trancpl-unfold-end}$  simp:  $\text{cdcl}_W\text{-merge-restart-no-step-cdcl}_W\text{-bj}$ )

```

If $\text{conflicting } S \neq \text{None}$, 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  $\text{conflicting-true-full-cdcl}_W\text{-iff-full-cdcl}_W\text{-merge}$ :
  assumes  $\text{conf!}: \text{conflicting } S = \text{None}$  and  $\text{lev}: \text{cdcl}_W\text{-M-level-inv } S$ 
  shows  $\text{full } \text{cdcl}_W S V \longleftrightarrow \text{full } \text{cdcl}_W\text{-merge-restart } S V$ 

```

proof

```

  assume  $\text{full}: \text{full } \text{cdcl}_W\text{-merge-restart } S V$ 
  then have  $\text{st}: \text{cdcl}_W^{**} S V$ 
    using  $\text{rtrancpl-mono[of } \text{cdcl}_W\text{-merge-restart } \text{cdcl}_W^{**}]$   $\text{cdcl}_W\text{-merge-restart-cdcl}_W$ 
    unfolding  $\text{full-def}$  by auto

  have  $n\text{-s}: \text{no-step } \text{cdcl}_W\text{-merge-restart } V$ 
    using  $\text{full}$  unfolding  $\text{full-def}$  by auto
  have  $n\text{-s-bj}: \text{no-step } \text{cdcl}_W\text{-bj } V$ 
    using  $\text{rtrancpl-cdcl}_W\text{-merge-restart-no-step-cdcl}_W\text{-bj}$   $\text{conf!}$   $\text{full}$  unfolding  $\text{full-def}$  by auto
  have  $\bigwedge S'. \text{conflict } V S' \implies \text{cdcl}_W\text{-M-level-inv } S'$ 
    using  $\text{cdcl}_W.\text{conflict}$   $\text{cdcl}_W\text{-consistent-inv}$   $\text{lev}$   $\text{rtrancpl-cdcl}_W\text{-consistent-inv}$   $\text{st}$  by blast
  then have  $\bigwedge S'. \text{conflict } V S' \implies \text{False}$ 
    using  $n\text{-s}$   $n\text{-s-bj}$   $\text{cdcl}_W\text{-bj-exists-normal-form}$   $\text{cdcl}_W\text{-merge-restart.simps}$  by meson
  then have  $n\text{-s-cdcl}_W: \text{no-step } \text{cdcl}_W V$ 
    using  $n\text{-s}$   $n\text{-s-bj}$  by (auto simp:  $\text{cdcl}_W.\text{simps}$   $\text{cdcl}_W\text{-o.simps}$   $\text{cdcl}_W\text{-merge-restart.simps}$ )
  then show  $\text{full } \text{cdcl}_W S V$  using  $\text{st}$  unfolding  $\text{full-def}$  by auto

next
  assume  $\text{full}: \text{full } \text{cdcl}_W S V$ 
  have  $\text{no-step } \text{cdcl}_W\text{-merge-restart } V$ 

```

```

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 ≠ 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 cdclW-merge-restart** S V
proof cases
  case fw
  then show ?thesis by fast
next
  case (bj T U)
  have no-step cdclW-bj V
  using full unfolding full-def by (meson cdclW-o.bj other)
  then have full cdclW-bj U V
  using ⟨ cdclW-bj** U V ⟩ unfolding full-def by auto
  then have cdclW-merge-restart T V
  using ⟨ conflict T U ⟩ cdclW-merge-restart.fw-r-conflict by blast
  then show ?thesis using ⟨ cdclW-merge-restart** S T ⟩ by auto
qed
ultimately show full cdclW-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

6.2.4 CDCL with Merge and Strategy

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 rtranclp-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-rtranclp-induct)

```

case base
then show ?case by (metis cdclW-stgy.conflict' full-unfold rtranclp.simps)
next
case (step T U) note st = this(2) and bj = this(1) and IH = this(3)[OF this(4)]
have no-step cdclW-cp T
  using bj by (auto simp add: cdclW-bj.simps cdclW-cp.simps elim!: rulesE)
consider
  (U) U = S'
| (U') U' where cdclW-bj U U' and cdclW-bj** U' S'
  using st by (metis converse-rtranclpE)

```

```

then show ?case
proof cases
  case U
  then show ?thesis
    using ⟨no-step cdclW-cp T⟩ cdclW-o.bj local.bj other' step.prem by (meson r-into-rtrancp)
next
  case U' note U' = this(1)
  have no-step cdclW-cp U
    using U' by (fastforce simp: cdclW-cp.simps cdclW-bj.simps elim: rulesE)
  then have full cdclW-cp U U
    by (simp add: full-unfold)
  then have cdclW-stgy T U
    using ⟨no-step cdclW-cp T⟩ cdclW-stgy.simps local.bj cdclW-o.bj by meson
  then show ?thesis using IH by auto
qed
qed

```

```

lemma cdclW-s'-is-rtrancp-cdclW-stgy:
  cdclW-s' S T  $\implies$  cdclW-stgy** S T
  apply (induction rule: cdclW-s'.induct)
  apply (auto intro: cdclW-stgy.intros)[]
  apply (meson decide other' r-into-rtrancp)
  by (metis full1-def rtrancp-cdclW-bj-full1-cdclp-cdclW-stgy trancp-into-rtrancp)

```

lemma cdcl_W-cp-cdcl_W-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
   $\vee (\exists U' U''. \text{full cdcl}_W\text{-cp } T' U'' \wedge \text{full1 cdcl}_W\text{-bj } U U' \wedge \text{full cdcl}_W\text{-cp } U' U''$ 
     $\wedge \text{cdcl}_W\text{-s}^{**} U U'')$ 
  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-bj** T T''
    using local.bj st by auto
  then have cdclW** T T''
    using rtrancp-cdclW-bj-rtrancp-cdclW by blast
  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
      using ⟨cdclW-bj++ T T'⟩ by (blast dest: trancpD)
    { assume cdclW-cp++ T U
      then obtain Z' where cdclW-cp T Z'

```

```

    by (meson tranclpD)
  then have False
    using ⟨cdclW-bj T Z⟩ by (fastforce simp: cdclW-bj.simps cdclW-cp.simps
      elim: rulesE)
}
then show ?thesis
  using full unfolding full-def rtranclp-unfold by blast
qed
obtain U'' where full cdclW-cp T'' U''
  using cdclW-cp-normalized-element-all-inv inv-T'' by blast
moreover then have cdclW-stgy** U U''
  by (metis ⟨T = U⟩ ⟨cdclW-bj++ T T'⟩ rtranclp-cdclW-bj-full1-cdclp-cdclW-stgy rtranclp-unfold)
moreover have cdclW-s*** U U''
proof -
  obtain ss :: 'st ⇒ 'st where
    f1: ∀ x2. (∃ v3. cdclW-cp x2 v3) = cdclW-cp x2 (ss x2)
  by maura
  have ¬ cdclW-cp U (ss U)
  by (meson full full-def)
  then show ?thesis
    using f1 by (metis (no-types) ⟨T = U⟩ ⟨full1 cdclW-bj T T'⟩ bj' calculation(1)
      r-into-rtranclp)
qed
ultimately show ?case
  using ⟨full1 cdclW-bj T T'⟩ ⟨full cdclW-cp T'' U''⟩ unfolding ⟨T = U⟩ by blast
qed

```

lemma cdcl_W-cp-cdcl_W-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
  ∨ (∃ U'. full1 cdclW-bj U U' ∧ (∀ U''. full cdclW-cp U' U'' ⟶ full cdclW-cp T' U''
    ∧ cdclW-s*** U U''))
using assms(2,1,3,4)
proof (induction rule: rtranclp-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 local.bj rtranclp.simps rtranclp-cdclW-bj-rtranclp-cdclW st)
  then have inv-T'': cdclW-all-struct-inv T''
  using inv rtranclp-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.premis(3))
  then have T = U
  proof -
    obtain Z where cdclW-bj T Z
    using ⟨cdclW-bj++ T T'⟩ by (blast dest: tranclpD)
    { assume cdclW-cp++ T U

```

```

    then obtain  $Z'$  where  $cdcl_W\text{-}cp\ T\ Z'$ 
      by (meson tranclpD)
    then have False
      using  $\langle cdcl_W\text{-}bj\ T\ Z \rangle$  by (fastforce simp:  $cdcl_W\text{-}bj.simps\ cdcl_W\text{-}cp.simps\ elim: rulesE$ )
  }
  then show ?thesis
    using full unfolding full-def rtranclp-unfold by blast
qed
{ fix  $U''$ 
  assume full  $cdcl_W\text{-}cp\ T''\ U''$ 
  moreover then have  $cdcl_W\text{-}stgy^{**}\ U\ U''$ 
    by (metis  $\langle T = U \rangle \langle cdcl_W\text{-}bj^{++}\ T\ T'' \rangle rtranclp\text{-}cdcl_W\text{-}bj\text{-}full1\text{-}cdclp\text{-}cdcl_W\text{-}stgy\ rtranclp\text{-}unfold$ )
  moreover have  $cdcl_W\text{-}s'^{**}\ U\ U''$ 
  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 assms(1) full-def)
    then show ?thesis
      using f1 by (metis (no-types)  $\langle T = U \rangle \langle full1\ cdcl_W\text{-}bj\ T\ T'' \rangle bj'\ calculation(1)$ 
        r-into-rtranclp)
  qed
  ultimately have  $full1\ cdcl_W\text{-}bj\ U\ T''$  and  $cdcl_W\text{-}s'^{**}\ T''\ U''$ 
    using  $\langle full1\ cdcl_W\text{-}bj\ T\ T'' \rangle \langle full\ cdcl_W\text{-}cp\ T''\ U'' \rangle$  unfolding  $\langle T = U \rangle$ 
    apply blast
    by (metis  $\langle full\ cdcl_W\text{-}cp\ T''\ U'' \rangle cdcl_W\text{-}s'.simps\ full\text{-}unfold\ rtranclp.simps$ )
  }
  then show ?case
    using  $\langle full1\ cdcl_W\text{-}bj\ T\ T'' \rangle$  full  $bj'$  unfolding  $\langle T = U \rangle$  full-def by (metis r-into-rtranclp)
qed

```

lemma $cdcl_W\text{-}stgy\text{-}cdcl_W\text{-}s'\text{-}connected$:

```

  assumes  $cdcl_W\text{-}stgy\ S\ U$  and  $cdcl_W\text{-}all\text{-}struct\text{-}inv\ S$ 
  shows  $cdcl_W\text{-}s'\ S\ U$ 
     $\vee (\exists U'. full1\ cdcl_W\text{-}bj\ U\ U' \wedge (\forall U''. full\ cdcl_W\text{-}cp\ U'\ U'' \longrightarrow cdcl_W\text{-}s'\ S\ U''))$ 
  using assms
proof (induction rule:  $cdcl_W\text{-}stgy.induct$ )
  case (conflict'  $T$ )
  then have  $cdcl_W\text{-}s'\ S\ T$ 
    using  $cdcl_W\text{-}s'.conflict'$  by blast
  then show ?case
    by blast
next
  case (other'  $T\ U$ ) note  $o = this(1)$  and  $n\text{-}s = this(2)$  and  $full = this(3)$  and  $inv = this(4)$ 
  show ?case
    using o
  proof cases
    case decide
    then show ?thesis using  $cdcl_W\text{-}s'.simps\ full\ n\text{-}s$  by blast
  next
    case bj
    have  $inv\text{-}T: cdcl_W\text{-}all\text{-}struct\text{-}inv\ T$ 
      using  $cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}inv\ o\ other\ other'.prems$  by blast
    consider
      (cp)  $full\ cdcl_W\text{-}cp\ T\ U$  and  $no\text{-}step\ cdcl_W\text{-}bj\ T$ 

```

```

| (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 tranclp.r-into-trancl)
    then show ?thesis
      using f1 full n-s by blast
    qed
  next
  case (fbj U')
  then have full1 cdclW-bj S U'
    using bj unfolding full1-def by auto
  moreover have no-step cdclW-cp S
    using n-s by blast
  moreover have T = U
    using full fbj unfolding full1-def full-def rtranclp-unfold
    by (force dest!: tranclpD simp:cdclW-bj.simps elim: rulesE)
  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-rtranclp-into-rtranclp 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-full1 local.bj n-s)
qed
qed

```

lemma *cdcl_W-stgy-cdcl_W-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-cdcl_W-stgy-connected-to-rtranclp-cdcl_W-s':*

```

assumes cdclW-stgy** S U and inv: cdclW-M-level-inv S
shows cdclW-s*** S U ∨ (∃ T. cdclW-s*** S T ∧ cdclW-bj++ T U ∧ conflicting U ≠ 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: cdcl_W-s' T V*

using *cdcl_W-s'.conflict'* **by** *blast*

obtain *ss :: 'st* **where**

*f3: S = T ∨ cdcl_W-stgy** S ss ∧ cdcl_W-stgy ss T*

by (*metis (full-types) rtranclp.simps st*)

obtain *ssa :: 'st* **where**

ssa: cdcl_W-cp T ssa

using *conflict'* **by** (*metis (no-types) full1-def tranclpD*)

have $\forall s. \neg \text{full } \text{cdcl}_W\text{-cp } s \text{ } T$

by (*meson ssa full-def*)

then have *S = T*


```

    by (metis (full-types) f3 ssa cdclW-stgy.cases 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 elim: rulesE)
    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 ≠ None
  using IH by blast
then show ?thesis
  proof cases
    case s'
    moreover
      have cdclW-M-level-inv T
        using inv local.step(1) rtranclp-cdclW-stgy-consistent-inv by auto
      then have full1 cdclW-bj T U
        using backtrack-is-full1-cdclW-bj backtrack by blast
      then have cdclW-s' T V
        using full bj' n-s by blast
      ultimately show ?thesis by auto
    next
    case (bj S') note S-S' = this(1) and bj-T = this(2)
    have no-step cdclW-cp S'
      using bj-T by (fastforce simp: cdclW-cp.simps cdclW-bj.simps dest!: tranclpD
        elim: rulesE)
    moreover
      have cdclW-M-level-inv T
        using inv local.step(1) rtranclp-cdclW-stgy-consistent-inv by auto
      then have full1 cdclW-bj T U
        using backtrack-is-full1-cdclW-bj backtrack by blast
      then have full1 cdclW-bj S' U
        using bj-T unfolding full1-def by fastforce
      ultimately have cdclW-s' S' V using full by (simp add: bj')
      then show ?thesis using S-S' by auto
    qed
  next
  case skip
  then have [simp]: U = V
    using full converse-rtranclpE unfolding full-def by (fastforce elim: rulesE)
  then have confl-V: conflicting V ≠ None
    using skip by (auto elim!: rulesE simp del: state-simp simp: state-eq-def)
  consider
    (s') cdclW-s'** S T
  | (bj) S' where cdclW-s'** S S' and cdclW-bj++ S' T and conflicting T ≠ None
  using IH by blast
then show ?thesis

```

```

proof cases
  case  $s'$ 
    show  $?thesis$  using  $s'$  confl-V skip by force
  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 tranclp.simps)
    then show  $?thesis$  using  $S-S'$  confl-V by auto
  qed
next
  case resolve
  then have  $[simp]:\ U = V$ 
    using full unfolding full-def rtranclp-unfold
    by  $(auto\ elim!:\ rulesE\ dest!:\ tranclpD$ 
       $simp\ del:\ state-simp\ simp:\ state-eq-def\ cdcl_W-cp.simps)$ 
  have confl-V: conflicting V ≠ None
    using resolve by (auto elim!:\ rulesE simp del:\ state-simp simp:\ state-eq-def)

consider
   $(s')\ cdcl_W-s'^{**}\ S\ T$ 
  |  $(bj)\ S'$  where  $cdcl_W-s'^{**}\ S\ S'$  and  $cdcl_W-bj^{++}\ S'\ T$  and conflicting T ≠ None
  using IH by blast
then show  $?thesis$ 
  proof cases
    case  $s'$ 
      have  $cdcl_W-bj^{++}\ T\ V$ 
      using resolve by force
      then show  $?thesis$  using  $s'$  confl-V by auto
    next
      case  $(bj\ S')$  note  $S-S' = this(1)$  and  $bj-T = this(2)$ 
      have  $cdcl_W-bj^{++}\ S'\ V$ 
        using resolve bj-T by (metis (U = V) cdcl_W-bj.resolve tranclp.simps)
      then show  $?thesis$  using confl-V S-S' by auto
    qed
  qed
qed
qed

lemma n-step-cdcl_W-stgy-iff-no-step-cdcl_W-cl-cdcl_W-o:
  assumes inv: cdcl_W-all-struct-inv S
  shows  $no\_step\ cdcl_W-s'\ S \longleftrightarrow no\_step\ cdcl_W-cp\ S \wedge no\_step\ cdcl_W-o\ S$  (is  $?S'\ S \longleftrightarrow ?C\ S \wedge ?O\ S)$ 
proof
  assume  $?C\ S \wedge ?O\ S$ 
  then show  $?S'\ S$ 
    by  $(auto\ simp:\ cdcl_W-s'.simps\ full1-def\ tranclp-unfold-begin)$ 
next
  assume  $n-s:\ ?S'\ S$ 
  have  $?C\ S$ 
  proof  $(rule\ ccontr)$ 
    assume  $\neg\ ?thesis$ 
    then obtain  $S'$  where  $cdcl_W-cp\ S\ S'$ 
      by auto
    then obtain  $T$  where  $full1\ cdcl_W-cp\ S\ T$ 
      using cdcl_W-cp-normalized-element-all-inv inv by (metis (no-types, lifting) full-unfold)
    then show False using  $n-s\ cdcl_W-s'.conflict'$  by blast
  qed

```

```

moreover have ?O S
proof (rule ccontr)
  assume  $\neg$  ?thesis
  then obtain S' where cdclW-o S S'
    by auto
  then obtain T where full1 cdclW-cp S' T
    using cdclW-cp-normalized-element-all-inv inv
    by (meson cdclW-all-struct-inv-def n-s
      cdclW-stgy-cdclW-s'-connected' cdclW-then-exists-cdclW-stgy-step )
  then show False using n-s by (meson (cdclW-o S S') cdclW-all-struct-inv-def
    cdclW-stgy-cdclW-s'-connected' cdclW-then-exists-cdclW-stgy-step inv)
qed
ultimately show ?C S  $\wedge$  ?O S by auto
qed

lemma cdclW-s'-trancpl-cdclW:
  cdclW-s' S S'  $\implies$  cdclW++ S S'
proof (induct rule: cdclW-s'.induct)
  case conflict'
  then show ?case
    by (simp add: full1-def trancpl-cdclW-cp-trancpl-cdclW)
next
  case decide'
  then show ?case
    using cdclW-stgy.simps cdclW-stgy-trancpl-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  $\Rightarrow$  'st  $\Rightarrow$  ('st  $\Rightarrow$  'st  $\Rightarrow$  bool)  $\Rightarrow$  'st where
     $\forall x0\ x1\ x2. (\exists v3. x2\ x1\ v3 \wedge x2^{**}\ v3\ x0) = (x2\ x1\ (ss\ x0\ x1\ x2) \wedge x2^{**}\ (ss\ x0\ x1\ x2)\ x0)$ 
    by moura
  then have f3:  $\forall p\ s\ sa. \neg p^{++}\ s\ sa \vee p\ s\ (ss\ sa\ s\ p) \wedge p^{**}\ (ss\ sa\ s\ p)\ sa$ 
    by (metis (full-types) trancplD)
  have cdclW-bj++ Sa S'a  $\wedge$  no-step cdclW-bj S'a
    using a2 by (simp add: full1-def)
  then have cdclW-bj Sa (ss S'a Sa cdclW-bj)  $\wedge$  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 rtrancpl-cdclW-bj-full1-cdclp-cdclW-stgy
      rtrancpl-cdclW-stgy-rtrancpl-cdclW rtrancpl-into-trancpl2)
qed

lemma trancpl-cdclW-s'-trancpl-cdclW:
  cdclW-s'++ S S'  $\implies$  cdclW++ S S'
  apply (induct rule: trancpl.induct)
  using cdclW-s'-trancpl-cdclW apply blast
  by (meson cdclW-s'-trancpl-cdclW trancpl-trans)

lemma rtrancpl-cdclW-s'-rtrancpl-cdclW:
  cdclW-s'** S S'  $\implies$  cdclW** S S'
  using rtrancpl-unfold[of cdclW-s' S S'] trancpl-cdclW-s'-trancpl-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  $\longleftrightarrow$  full cdclW-s' S T (is ?S  $\longleftrightarrow$  ?S')
proof
  assume ?S'

```

```

then have  $cdcl_W^{**} S T$ 
  using  $rtrancp\text{-}cdcl_W\text{-}s'\text{-}rtrancp\text{-}cdcl_W[of\ S\ T]$  unfolding full-def by blast
then have  $inv': cdcl_W\text{-}all\text{-}struct\text{-}inv\ T$ 
  using  $rtrancp\text{-}cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}inv\ inv$  by blast
have  $cdcl_W\text{-}stgy^{**} S T$ 
  using  $\langle ?S' \rangle$  unfolding full-def
  using  $cdcl_W\text{-}s'\text{-}is\text{-}rtrancp\text{-}cdcl_W\text{-}stgy\ rtrancp\text{-}mono[of\ cdcl_W\text{-}s'\ cdcl_W\text{-}stgy^{**}]$  by auto
then show  $?S$ 
  using  $\langle ?S' \rangle\ inv'\ cdcl_W\text{-}stgy\text{-}cdcl_W\text{-}s'\text{-}connected'$  unfolding full-def by blast
next
assume  $?S$ 
then have  $inv\text{-}T: cdcl_W\text{-}all\text{-}struct\text{-}inv\ T$ 
  by (metis assms full-def rtrancp-cdcl_W-all-struct-inv-inv rtrancp-cdcl_W-stgy-rtrancp-cdcl_W)

consider
  ( $s'$ )  $cdcl_W\text{-}s'^{**} S T$ 
| ( $st$ )  $S'$  where  $cdcl_W\text{-}s'^{**} S S'$  and  $cdcl_W\text{-}bj^{++} S' T$  and conflicting  $T \neq None$ 
  using  $rtrancp\text{-}cdcl_W\text{-}stgy\text{-}connected\text{-}to\text{-}rtrancp\text{-}cdcl_W\text{-}s'[of\ S\ T]\ inv\ \langle ?S \rangle$ 
  unfolding full-def  $cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def$ 
  by blast
then show  $?S'$ 
  proof cases
  case  $s'$ 
  have  $no\text{-}step\ cdcl_W\text{-}s'\ T$ 
    using  $\langle full\ cdcl_W\text{-}stgy\ S\ T \rangle$  unfolding full-def
    by (metis  $cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def\ cdcl_W\text{-}s'E\ cdcl_W\text{-}stgy.conflict'$ 
       $cdcl_W\text{-}then\text{-}exists\text{-}cdcl_W\text{-}stgy\text{-}step\ inv\text{-}T\ n\text{-}step\text{-}cdcl_W\text{-}stgy\text{-}iff\text{-}no\text{-}step\text{-}cdcl_W\text{-}cl\text{-}cdcl_W\text{-}o$ )
  then show  $?thesis$ 
    using  $s'$  unfolding full-def by blast
  next
  case ( $st\ S'$ )
  have  $full\ cdcl_W\text{-}cp\ T\ T$ 
    using  $option\text{-}full\text{-}cdcl_W\text{-}cp\ st(3)$  by blast
  moreover
    have  $n\text{-}s: no\text{-}step\ cdcl_W\text{-}bj\ T$ 
      by (metis  $\langle full\ cdcl_W\text{-}stgy\ S\ T \rangle\ bj\ inv\text{-}T\ cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def$ 
         $cdcl_W\text{-}then\text{-}exists\text{-}cdcl_W\text{-}stgy\text{-}step\ full\text{-}def$ )
    then have  $full1\ cdcl_W\text{-}bj\ S'\ T$ 
      using  $st(2)$  unfolding full1-def by blast
  moreover have  $no\text{-}step\ cdcl_W\text{-}cp\ S'$ 
    using  $st(2)$  by (fastforce dest!: trancpD simp: cdcl_W-cp.simps cdcl_W-bj.simps
      elim: rulesE)
  ultimately have  $cdcl_W\text{-}s'\ S'\ T$ 
    using  $cdcl_W\text{-}s'.bj'[of\ S'\ T\ T]$  by blast
  then have  $cdcl_W\text{-}s'^{**} S T$ 
    using  $st(1)$  by auto
  moreover have  $no\text{-}step\ cdcl_W\text{-}s'\ T$ 
    using  $inv\text{-}T\ \langle full\ cdcl_W\text{-}cp\ T\ T \rangle\ \langle full\ cdcl_W\text{-}stgy\ S\ T \rangle$  unfolding full-def
    by (metis  $cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}def\ cdcl_W\text{-}then\text{-}exists\text{-}cdcl_W\text{-}stgy\text{-}step$ 
       $n\text{-}step\text{-}cdcl_W\text{-}stgy\text{-}iff\text{-}no\text{-}step\text{-}cdcl_W\text{-}cl\text{-}cdcl_W\text{-}o$ )
  ultimately show  $?thesis$ 
    unfolding full-def by blast
qed
qed

```

lemma *conflict-step-cdcl_W-stgy-step:*

```

assumes
  conflict S T
  cdclW-all-struct-inv S
shows  $\exists T. \text{cdcl}_W\text{-stgy } S \ T$ 
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  $\exists T. \text{cdcl}_W\text{-stgy } S \ T$ 
proof –
  obtain U where full cdclW-cp T U
    using cdclW-cp-normalized-element-all-inv by (meson assms(1) assms(2) cdclW-all-struct-inv-inv
      cdclW-cp-normalized-element-all-inv decide other)
  then show ?thesis
    by (metis assms cdclW-cp-normalized-element-all-inv cdclW-stgy.conflict' decide full-unfold
      other')
qed

lemma rtranclp-cdclW-cp-conflicting-Some:
  cdclW-cp** S T  $\implies$  conflicting S = Some D  $\implies$  S = T
  using rtranclpD tranclpD by fastforce

inductive cdclW-merge-cp :: 'st  $\Rightarrow$  'st  $\Rightarrow$  bool for S :: 'st where
  conflict': conflict S T  $\implies$  full cdclW-bj T U  $\implies$  cdclW-merge-cp S U |
  propagate': propagate++ S S'  $\implies$  cdclW-merge-cp S S'

lemma cdclW-merge-restart-cases[consumes 1, case-names conflict propagate]:
assumes
  cdclW-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 cdclW-merge-cp.simps by auto

lemma cdclW-merge-cp-tranclp-cdclW-merge:
  cdclW-merge-cp S T  $\implies$  cdclW-merge++ S T
apply (induction rule: cdclW-merge-cp.induct)
  using cdclW-merge.simps apply auto[1]
using tranclp-mono[of propagate cdclW-merge] fw-propagate by blast

lemma rtranclp-cdclW-merge-cp-rtranclp-cdclW:
  cdclW-merge-cp** S T  $\implies$  cdclW** S T
apply (induction rule: rtranclp-induct)
apply simp
unfolding cdclW-merge-cp.simps by (meson cdclW-merge-restart-cdclW fw-r-conflict
  rtranclp-propagate-is-rtranclp-cdclW rtranclp-trans tranclp-into-rtranclp)

lemma full1-cdclW-bj-no-step-cdclW-bj:

```

$full1\ cdcl_W\text{-}bj\ S\ T \implies no\text{-}step\ cdcl_W\text{-}cp\ S$
unfolding $full1\text{-}def$ **by** (*metis rtrancp-unfold cdcl_W-cp-conflicting-not-empty option.exhaust rtrancp-cdcl_W-merge-restart-no-step-cdcl_W-bj trancpD*)

Full Transformation

inductive $cdcl_W\text{-}s'\text{-}without\text{-}decide$ **where**

$conflict'\text{-}without\text{-}decide[intro]: full1\ cdcl_W\text{-}cp\ S\ S' \implies cdcl_W\text{-}s'\text{-}without\text{-}decide\ S\ S' \mid$
 $bj'\text{-}without\text{-}decide[intro]: full1\ cdcl_W\text{-}bj\ S\ S' \implies no\text{-}step\ cdcl_W\text{-}cp\ S \implies full\ cdcl_W\text{-}cp\ S'\ S''$
 $\implies cdcl_W\text{-}s'\text{-}without\text{-}decide\ S\ S''$

lemma $rtrancp\text{-}cdcl_W\text{-}s'\text{-}without\text{-}decide\text{-}rtrancp\text{-}cdcl_W$:

$cdcl_W\text{-}s'\text{-}without\text{-}decide^{**}\ S\ T \implies cdcl_W^{**}\ S\ T$

apply (*induction rule: rtrancp-induct*)

apply *simp*

by (*meson cdcl_W-s'.simps cdcl_W-s'-trancp-cdcl_W cdcl_W-s'-without-decide.simps rtrancp-trancp-trancp trancp-into-rtrancp*)

lemma $rtrancp\text{-}cdcl_W\text{-}s'\text{-}without\text{-}decide\text{-}rtrancp\text{-}cdcl_W\text{-}s'$:

$cdcl_W\text{-}s'\text{-}without\text{-}decide^{**}\ S\ T \implies cdcl_W\text{-}s'^{**}\ S\ T$

proof (*induction rule: rtrancp-induct*)

case *base*

then show *?case by simp*

next

case (*step y z*) **note** $a2 = this(2)$ **and** $a1 = this(3)$

have $cdcl_W\text{-}s'\ y\ z$

using $a2$ **by** (*metis (no-types) bj' cdcl_W-s'.conflict' cdcl_W-s'-without-decide.cases*)

then show $cdcl_W\text{-}s'^{**}\ S\ z$

using $a1$ **by** (*meson r-into-rtrancp rtrancp-trans*)

qed

lemma $rtrancp\text{-}cdcl_W\text{-}merge\text{-}cp\text{-}is\text{-}rtrancp\text{-}cdcl_W\text{-}s'\text{-}without\text{-}decide$:

assumes

$cdcl_W\text{-}merge\text{-}cp^{**}\ S\ V$

$conflicting\ S = None$

shows

$(cdcl_W\text{-}s'\text{-}without\text{-}decide^{**}\ S\ V)$

$\vee (\exists T. cdcl_W\text{-}s'\text{-}without\text{-}decide^{**}\ S\ T \wedge propagate^{++}\ T\ V)$

$\vee (\exists T\ U. cdcl_W\text{-}s'\text{-}without\text{-}decide^{**}\ S\ T \wedge full1\ cdcl_W\text{-}bj\ T\ U \wedge propagate^{**}\ U\ V)$

using *assms*

proof (*induction rule: rtrancp-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: cdcl_W-merge-restart-cases*)

case *propagate*

then show *?thesis using IH by (meson rtrancp-trancp-trancp trancp-into-rtrancp)*

next

case (*conflict U'*) **note** $confl = this(1)$ **and** $bj = this(2)$

have $full1\text{-}U\text{-}U': full1\ cdcl_W\text{-}cp\ U\ U'$

by (*simp add: conflict-is-full1-cdcl_W-cp local.conflict(1)*)

consider

$(s')\ cdcl_W\text{-}s'\text{-}without\text{-}decide^{**}\ S\ U$

$\mid (propa)\ T' \textbf{ where } cdcl_W\text{-}s'\text{-}without\text{-}decide^{**}\ S\ T' \textbf{ and } propagate^{++}\ T'\ U$

```

| (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 rtrancp-mono[of propagate cdclW-cp] T'-U cdclW-cp.propagate' full1-U-U'
  rtrancp-full1I[of cdclW-cp T'] by (metis (full-types) predicate2D predicate2I
    trancp-into-rtrancp)
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' using bj unfolding full-unfold by blast
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 rtrancp-mono[of propagate cdclW-cp] T''-U cdclW-cp.propagate' full1-U-U'
  rtrancp-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' rtrancp.intros(2)[of - S T' U] by blast
then show ?thesis
  using local.bj unfolding full-unfold by blast
qed
qed
qed

lemma rtrancp-cdclW-s'-without-decide-is-rtrancp-cdclW-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 tranclp-cdclW-cp-propagate-with-conflict-or-not[of U V]
    conflict by (auto dest!: tranclpD simp: rtranclp-unfold elim: rulesE)
  then have cdclW-merge-cp** S U using IH by (auto elim: rulesE
    simp del: state-simp simp: state-eq-def)
  consider
    (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[OF rt] unfolding rtranclp-unfold
  by fastforce
then show ?thesis
proof cases
  case propa
  then have cdclW-merge-cp U V
    by (auto intro: cdclW-merge-cp.intros)
  moreover have conflicting V = None
    using propa unfolding tranclp-unfold-end by (auto elim: rulesE)
  ultimately show ?thesis using ⟨cdclW-merge-cp** S U⟩ by (auto elim!: rulesE
    simp del: state-simp simp: state-eq-def)
  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 intro: cdclW-merge-cp.intros)
  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
    elim: rulesE)
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 (blast intro: cdclW-merge-cp.intros)

```



```

    moreover have conflicting V = None
      using propa unfolding tranclp-unfold-end by (auto elim: rulesE)
    ultimately show ?thesis using S-U' by (auto elim: rulesE
      simp del: state-simp simp: state-eq-def)
  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 (blast intro: cdclW-merge-cp.intros)
    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-cdclW-s'-no-ste-cdclW-merge-cp:
  assumes
    cdclW-all-struct-inv S
    conflicting S = None
    no-step cdclW-s' S
  shows no-step cdclW-merge-cp S
  using assms apply (auto simp: cdclW-s'.sims cdclW-merge-cp.sims)
  using conflict-is-full1-cdclW-cp apply blast
  using cdclW-cp-normalized-element-all-inv cdclW-cp.propagate' by (metis cdclW-cp.propagate'
    full-unfold tranclpD)

```

The *no-step decide S* is needed, since *cdcl_W-merge-cp* is *cdcl_W-s'* without *decide*.

```

lemma conflicting-true-no-step-cdclW-merge-cp-no-step-s'-without-decide:

```

```

  assumes
    confl: conflicting S = None and
    inv: cdclW-M-level-inv S and
    n-s: no-step cdclW-merge-cp S
  shows no-step cdclW-s'-without-decide S
proof (rule ccontr)
  assume ¬ no-step cdclW-s'-without-decide S
  then obtain T where
    cdclW: cdclW-s'-without-decide S T
    by auto
  then have inv-T: cdclW-M-level-inv T
    using rtranclp-cdclW-s'-without-decide-rtranclp-cdclW[of S T]
    rtranclp-cdclW-consistent-inv inv by blast
  from cdclW show False
proof cases
  case conflict'-without-decide
  have no-step propagate S
    using n-s by (blast intro: cdclW-merge-cp.intros)
  then have conflict S T
    using local.conflict' tranclp-cdclW-cp-propagate-with-conflict-or-not[of S T]
    local.conflict'-without-decide unfolding full1-def rtranclp-unfold
    by (metis tranclp-unfold-begin)

```

```

    moreover
      then obtain  $T'$  where  $\text{full } \text{cdcl}_W\text{-bj } T \ T'$ 
      using  $\text{cdcl}_W\text{-bj-exists-normal-form inv-}T$  by blast
    ultimately show  $\text{False}$  using  $\text{cdcl}_W\text{-merge-cp.conflict' n-s}$  by meson
  next
    case ( $\text{bj}'\text{-without-decide } S'$ )
    then show  $?thesis$ 
      using  $\text{confl unfolding full1-def}$  by ( $\text{fastforce simp: cdcl}_W\text{-bj.simps dest: tranclpD}$ 
         $\text{elim: rulesE}$ )
  qed
qed

lemma conflicting-true-no-step-s'-without-decide-no-step-cdclW-merge-cp:
  assumes
     $\text{inv: cdcl}_W\text{-all-struct-inv } S$  and
     $\text{n-s: no-step cdcl}_W\text{-s'-without-decide } S$ 
  shows  $\text{no-step cdcl}_W\text{-merge-cp } S$ 
proof (rule ccontr)
  assume  $\neg ?thesis$ 
  then obtain  $T$  where  $\text{cdcl}_W\text{-merge-cp } S \ T$ 
    by auto
  then show  $\text{False}$ 
  proof cases
    case ( $\text{conflict' } S'$ )
    then show  $\text{False}$  using  $\text{n-s conflict'-without-decide conflict-is-full1-cdcl}_W\text{-cp}$  by blast
  next
    case  $\text{propagate'}$ 
    moreover
      have  $\text{cdcl}_W\text{-all-struct-inv } T$ 
        using  $\text{inv}$  by ( $\text{meson local.propagate' rtranclp-cdcl}_W\text{-all-struct-inv-inv}$ 
           $\text{rtranclp-propagate-is-rtranclp-cdcl}_W \text{ tranclp-into-rtranclp}$ )
      then obtain  $U$  where  $\text{full cdcl}_W\text{-cp } T \ U$ 
        using  $\text{cdcl}_W\text{-cp-normalized-element-all-inv}$  by auto
      ultimately have  $\text{full1 cdcl}_W\text{-cp } S \ U$ 
        using  $\text{tranclp-full-full1[of cdcl}_W\text{-cp } S \ T \ U] \text{ cdcl}_W\text{-cp.propagate'}$ 
           $\text{tranclp-mono[of propagate cdcl}_W\text{-cp]}$  by blast
      then show  $\text{False}$  using  $\text{conflict'-without-decide n-s}$  by blast
    qed
  qed

lemma no-step-cdclW-merge-cp-no-step-cdclW-cp:
   $\text{no-step cdcl}_W\text{-merge-cp } S \implies \text{cdcl}_W\text{-M-level-inv } S \implies \text{no-step cdcl}_W\text{-cp } S$ 
  using  $\text{cdcl}_W\text{-bj-exists-normal-form cdcl}_W\text{-consistent-inv[OF cdcl}_W\text{.conflict, of } S]$ 
  by ( $\text{metis cdcl}_W\text{-cp.cases cdcl}_W\text{-merge-cp.simps tranclp.intros(1)}$ )

lemma conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj:
  assumes
     $\text{conflicting } S = \text{None}$  and
     $\text{cdcl}_W\text{-merge-cp}^{**} S \ T$ 
  shows  $\text{no-step cdcl}_W\text{-bj } T$ 
  using  $\text{assms(2,1)}$  by ( $\text{induction}$ )
  ( $\text{fastforce simp: cdcl}_W\text{-merge-cp.simps full-def tranclp-unfold-end cdcl}_W\text{-bj.simps}$ 
     $\text{elim: rulesE}$ ) +

lemma conflicting-true-full-cdclW-merge-cp-iff-full-cdclW-s'-without-decode:
  assumes

```

confl: conflicting $S = \text{None}$ and
inv: $\text{cdcl}_W\text{-all-struct-inv } S$
shows
 $\text{full } \text{cdcl}_W\text{-merge-cp } S \ V \longleftrightarrow \text{full } \text{cdcl}_W\text{-s'-without-decide } S \ V \text{ (is } ?fw \longleftrightarrow ?s')$

proof

assume $?fw$
then have st : $\text{cdcl}_W\text{-merge-cp}^{**} \ S \ V$ and $n\text{-s}$: $\text{no-step } \text{cdcl}_W\text{-merge-cp } V$
unfolding full-def **by** blast+
have $\text{inv-}V$: $\text{cdcl}_W\text{-all-struct-inv } V$
using $\text{rtrancpl-cdcl}_W\text{-merge-cp-rtrancpl-cdcl}_W[\text{of } S \ V] \text{ } \langle ?fw \rangle$ **unfolding** full-def
by ($\text{simp add: inv rtrancpl-cdcl}_W\text{-all-struct-inv-inv}$)
consider
 $(s') \text{cdcl}_W\text{-s'-without-decide}^{**} \ S \ V$
 $| \text{ (propa) } T \text{ where } \text{cdcl}_W\text{-s'-without-decide}^{**} \ S \ T \text{ and } \text{propagate}^{++} \ T \ V$
 $| \text{ (bj) } T \ U \text{ where } \text{cdcl}_W\text{-s'-without-decide}^{**} \ S \ T \text{ and } \text{full1 } \text{cdcl}_W\text{-bj } T \ U \text{ and } \text{propagate}^{**} \ U \ V$
using $\text{rtrancpl-cdcl}_W\text{-merge-cp-is-rtrancpl-cdcl}_W\text{-s'-without-decide } \text{confl } st \ n\text{-s}$ **by** metis
then have $\text{cdcl}_W\text{-s'-without-decide}^{**} \ S \ V$
proof cases
case s'
then show $?thesis$.
next
case propa **note** $s' = \text{this}(1)$ and $\text{propa} = \text{this}(2)$
have $\text{no-step } \text{cdcl}_W\text{-cp } V$
using $\text{no-step-cdcl}_W\text{-merge-cp-no-step-cdcl}_W\text{-cp } n\text{-s } \text{inv-}V$
unfolding $\text{cdcl}_W\text{-all-struct-inv-def}$ **by** blast
then have $\text{full1 } \text{cdcl}_W\text{-cp } T \ V$
using $\text{propa } \text{trancpl-mono}[\text{of } \text{propagate } \text{cdcl}_W\text{-cp}] \ \text{cdcl}_W\text{-cp.propagate'}$ **unfolding** full1-def
by blast
then have $\text{cdcl}_W\text{-s'-without-decide } T \ V$
using $\text{conflict'-without-decide}$ **by** blast
then show $?thesis$ **using** s' **by** auto
next
case bj **note** $s' = \text{this}(1)$ and $\text{bj} = \text{this}(2)$ and $\text{propa} = \text{this}(3)$
have $\text{no-step } \text{cdcl}_W\text{-cp } V$
using $\text{no-step-cdcl}_W\text{-merge-cp-no-step-cdcl}_W\text{-cp } n\text{-s } \text{inv-}V$
unfolding $\text{cdcl}_W\text{-all-struct-inv-def}$ **by** blast
then have $\text{full } \text{cdcl}_W\text{-cp } U \ V$
using $\text{propa } \text{rtrancpl-mono}[\text{of } \text{propagate } \text{cdcl}_W\text{-cp}] \ \text{cdcl}_W\text{-cp.propagate'}$ **unfolding** full-def
by blast
moreover have $\text{no-step } \text{cdcl}_W\text{-cp } T$
using bj **unfolding** full1-def **by** ($\text{fastforce } \text{dest!} \text{: } \text{trancplD } \text{simp:cdcl}_W\text{-bj.simps elim: rulesE}$)
ultimately have $\text{cdcl}_W\text{-s'-without-decide } T \ V$
using $\text{bj'-without-decide}[\text{of } T \ U \ V] \ \text{bj}$ **by** blast
then show $?thesis$ **using** s' **by** auto
qed
moreover have $\text{no-step } \text{cdcl}_W\text{-s'-without-decide } V$
proof ($\text{cases } \text{conflicting } V = \text{None}$)
case False
{ fix $ss :: 'st$
have $\text{ff1: } \forall s \ sa. \neg \text{cdcl}_W\text{-s' } s \ sa \vee \text{full1 } \text{cdcl}_W\text{-cp } s \ sa$
 $\vee (\exists sb. \text{decide } s \ sb \wedge \text{no-step } \text{cdcl}_W\text{-cp } s \wedge \text{full } \text{cdcl}_W\text{-cp } sb \ sa)$
 $\vee (\exists sb. \text{full1 } \text{cdcl}_W\text{-bj } s \ sb \wedge \text{no-step } \text{cdcl}_W\text{-cp } s \wedge \text{full } \text{cdcl}_W\text{-cp } sb \ sa)$
by ($\text{metis } \text{cdcl}_W\text{-s'.cases}$)
have $\text{ff2: } (\forall p \ s \ sa. \neg \text{full1 } p \ (s::'st) \ sa \vee p^{++} \ s \ sa \wedge \text{no-step } p \ sa)$
 $\wedge (\forall p \ s \ sa. (\neg p^{++} \ (s::'st) \ sa \vee (\exists s. p \ sa \ s)) \vee \text{full1 } p \ s \ sa)$
by (meson full1-def)

```

obtain ssa :: ('st ⇒ 'st ⇒ bool) ⇒ 'st ⇒ 'st ⇒ 'st where
  ff3: ∀ p s sa. ¬ p++ s sa ∨ p s (ssa p s sa) ∧ p** (ssa p s sa) sa
  by (metis (no-types) tranclpD)
then have a3: ¬ cdclW-cp++ V ss
  using False by (metis option-full-cdclW-cp full-def)
have ∧s. ¬ cdclW-bj++ V s
  using ff3 False by (metis confl st
    conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj)
then have ¬ cdclW-s'-without-decide V ss
  using ff1 a3 ff2 by (metis cdclW-s'-without-decide.cases)
}
then show ?thesis
  by fastforce
next
  case True
  then show ?thesis
    using conflicting-true-no-step-cdclW-merge-cp-no-step-s'-without-decide n-s inv-V
    unfolding cdclW-all-struct-inv-def by simp
qed
ultimately show ?s' unfolding full-def by blast
next
assume s': ?s'
then have st: cdclW-s'-without-decide** S V and n-s: no-step cdclW-s'-without-decide V
  unfolding full-def by auto
then have cdclW** S V
  using rtranclp-cdclW-s'-without-decide-rtranclp-cdclW st by blast
then have inv-V: cdclW-all-struct-inv V using inv rtranclp-cdclW-all-struct-inv-inv by blast
then have n-s-cp-V: no-step cdclW-cp V
  using cdclW-cp-normalized-element-all-inv[of V] full-fullI[of cdclW-cp V] n-s
  conflict'-without-decide conflicting-true-no-step-s'-without-decide-no-step-cdclW-merge-cp
  no-step-cdclW-merge-cp-no-step-cdclW-cp
  unfolding cdclW-all-struct-inv-def by presburger
have n-s-bj: no-step cdclW-bj V
proof (rule ccontr)
  assume ¬ ?thesis
  then obtain W where W: cdclW-bj V W by blast
  have cdclW-all-struct-inv W
    using W cdclW.simps cdclW-all-struct-inv-inv inv-V by blast
  then obtain W' where full1 cdclW-bj V W'
    using cdclW-bj-exists-normal-form[of W] full-fullI[of cdclW-bj V W] W
    unfolding cdclW-all-struct-inv-def
    by blast
moreover
  then have cdclW++ V W'
    using tranclp-mono[of cdclW-bj cdclW] cdclW.other cdclW-o.bj unfolding full1-def by blast
  then have cdclW-all-struct-inv W'
    by (meson inv-V rtranclp-cdclW-all-struct-inv-inv tranclp-into-rtranclp)
  then obtain X where full cdclW-cp W' X
    using cdclW-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) cdclW-merge-cp** S V and conflicting V = None
  | (cp-false) cdclW-merge-cp** S V and conflicting V ≠ None and no-step cdclW-cp V and
    no-step cdclW-bj V

```

```

| (cp-conf) T where cdclW-merge-cp** S T conflict T V
using rtrancp-cdclW-s'-without-decide-is-rtrancp-cdclW-merge-cp[of S V] confl
unfolding full-def by meson
then have cdclW-merge-cp** S V
proof cases
  case cp-conf note S-T = this(1) and conf-V = this(2)
  have full cdclW-bj V V
    using conf-V n-s-bj unfolding full-def by fast
  then have cdclW-merge-cp T V
    using cdclW-merge-cp.conflict' conf-V by auto
  then show ?thesis using S-T by auto
qed fast+
moreover
  then have cdclW** S V using rtrancp-cdclW-merge-cp-rtrancp-cdclW by blast
  then have cdclW-all-struct-inv V
    using inv rtrancp-cdclW-all-struct-inv-inv by blast
  then have no-step cdclW-merge-cp V
    using conflicting-true-no-step-s'-without-decide-no-step-cdclW-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

 conf: 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-decide inv

by simp

then show ?thesis **unfolding** full-unfold full1-def trancp-unfold-begin **by** blast

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!: trancpD simp: cdcl_W-merge-cp.simps elim: rulesE)

then show ?thesis

using conflicting-true-full1-cdcl_W-merge-cp-iff-full1-cdcl_W-s'-without-decode fw inv **by** simp

qed

inductive cdcl_W-merge-stgy **for** S :: 'st **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-trancp-cdcl_W-merge:

assumes fw: cdcl_W-merge-stgy S T

shows cdcl_W-merge⁺⁺ S T

```

proof -
{ fix S T
  assume full1 cdclW-merge-cp S T
  then have cdclW-merge++ S T
    using tranclp-mono[of cdclW-merge-cp cdclW-merge++] cdclW-merge-cp-tranclp-cdclW-merge
    unfolding full1-def
    by auto
} note full1-cdclW-merge-cp-cdclW-merge = this
show ?thesis
  using fw
  apply (induction rule: cdclW-merge-stgy.induct)
    using full1-cdclW-merge-cp-cdclW-merge apply simp
  unfolding full-unfold by (auto dest!: full1-cdclW-merge-cp-cdclW-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
 $\bigwedge T. \text{decide } S \ T \implies \text{no-step } \text{cdcl}_W\text{-merge-cp } S \implies \text{full } \text{cdcl}_W\text{-merge-cp } T \ U \implies P$
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-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 *rtrancpl-mono*[*of cdcl_W-s'-w cdcl_W***] *cdcl_W-s'-w-rtrancpl-cdcl_W* **by** *auto*

lemma *no-step-cdcl_W-cp-no-step-cdcl_W-s'-without-decide*:
assumes *no-step cdcl_W-cp S and conflicting S = 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 trancplD*
conflicting-true-no-step-cdcl_W-merge-cp-no-step-s'-without-decide)

lemma *no-step-cdcl_W-cp-no-step-cdcl_W-merge-restart*:
assumes *no-step cdcl_W-cp S and conflicting S = 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 trancplD*)

lemma *after-cdcl_W-s'-without-decide-no-step-cdcl_W-cp*:
assumes *cdcl_W-s'-without-decide S T*
shows *no-step cdcl_W-cp T*
using *assms* **by** (*induction rule: cdcl_W-s'-without-decide.induct*) (*auto simp: full1-def full-def*)

lemma *no-step-cdcl_W-s'-without-decide-no-step-cdcl_W-cp*:
cdcl_W-all-struct-inv S \implies no-step cdcl_W-s'-without-decide S \implies no-step cdcl_W-cp S
by (*simp add: conflicting-true-no-step-s'-without-decide-no-step-cdcl_W-merge-cp*
no-step-cdcl_W-merge-cp-no-step-cdcl_W-cp cdcl_W-all-struct-inv-def)

lemma *after-cdcl_W-s'-w-no-step-cdcl_W-cp*:
assumes *cdcl_W-s'-w S T and cdcl_W-all-struct-inv S*
shows *no-step cdcl_W-cp T*
using *assms*

proof (*induction rule: cdcl_W-s'-w.induct*)
case *conflict'*
then show *?case*
by (*auto simp: full1-def trancpl-unfold-end after-cdcl_W-s'-without-decide-no-step-cdcl_W-cp*)

next
case (*decide' S T U*)
moreover
then have *cdcl_W** S U*
using *rtrancpl-cdcl_W-s'-without-decide-rtrancpl-cdcl_W[of T U] cdcl_W.other[of S T]*
cdcl_W-o.decide unfolding full-def by auto
then have *cdcl_W-all-struct-inv U*
using *decide'.prems rtrancpl-cdcl_W-all-struct-inv-inv by blast*
ultimately show *?case*
using *no-step-cdcl_W-s'-without-decide-no-step-cdcl_W-cp unfolding full-def by blast*

qed

lemma *rtrancpl-cdcl_W-s'-w-no-step-cdcl_W-cp-or-eq*:
assumes *cdcl_W-s'-w** S T and cdcl_W-all-struct-inv S*
shows *S = T \vee no-step cdcl_W-cp T*
using *assms*

proof (*induction rule: rtrancpl-induct*)
case *base*
then show *?case by simp*

next
case (*step T U*)
moreover have *cdcl_W-all-struct-inv T*
using *rtrancpl-cdcl_W-s'-w-rtrancpl-cdcl_W[of S U] assms(2) rtrancpl-cdcl_W-all-struct-inv-inv*
rtrancpl-cdcl_W-s'-w-rtrancpl-cdcl_W step.hyps(1) by blast
ultimately show *?case using after-cdcl_W-s'-w-no-step-cdcl_W-cp by fast*

qed

lemma *rtrancpl-cdcl_W-merge-stgy'-no-step-cdcl_W-cp-or-eq*:
assumes *cdcl_W-merge-stgy** S T* **and** *inv: cdcl_W-all-struct-inv S*
shows $S = T \vee \text{no-step } \text{cdcl}_W\text{-cp } T$
using *assms*
proof (*induction rule: rtrancpl-induct*)
case *base*
then show *?case* **by** *simp*
next
case (*step T U*)
moreover have *cdcl_W-all-struct-inv T*
using *rtrancpl-cdcl_W-merge-stgy-rtrancpl-cdcl_W[of S U] assms(2) rtrancpl-cdcl_W-all-struct-inv-inv*
rtrancpl-cdcl_W-s'-w-rtrancpl-cdcl_W step.hyps(1)
by (*meson rtrancpl-cdcl_W-merge-stgy-rtrancpl-cdcl_W*)
ultimately show *?case*
using *after-cdcl_W-s'-w-no-step-cdcl_W-cp inv unfolding cdcl_W-all-struct-inv-def*
by (*metis cdcl_W-all-struct-inv-def cdcl_W-merge-stgy.simps full1-def full-def*
no-step-cdcl_W-merge-cp-no-step-cdcl_W-cp rtrancpl-cdcl_W-all-struct-inv-inv
rtrancpl-cdcl_W-merge-stgy-rtrancpl-cdcl_W trancpl.intros(1) trancpl-into-rtrancpl)
qed

lemma *no-step-cdcl_W-s'-without-decide-no-step-cdcl_W-bj*:
assumes *no-step cdcl_W-s'-without-decide S* **and** *inv: cdcl_W-all-struct-inv S*
shows *no-step cdcl_W-bj S*
proof (*rule ccontr*)
assume $\neg ?thesis$
then obtain *T* **where** *S-T: cdcl_W-bj S T*
by *auto*
have *cdcl_W-all-struct-inv T*
using *S-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-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** *blast*
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-T* **by** (*auto simp: cdcl_W-bj.simps elim: rulesE*)
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-s'^{/*} R V **and**
conflicting R = None **and**
inv: cdcl_W-all-struct-inv R
shows (cdcl_W-merge-stgy** R V \wedge conflicting V = None)
 \vee (cdcl_W-merge-stgy** R V \wedge conflicting V \neq None \wedge no-step cdcl_W-bj V)
 \vee (\exists S T U. cdcl_W-merge-stgy** R S \wedge no-step cdcl_W-merge-cp S \wedge decide S T
 \wedge cdcl_W-merge-cp** T U \wedge conflict U V)
 \vee (\exists S T. cdcl_W-merge-stgy** R S \wedge no-step cdcl_W-merge-cp S \wedge decide S T
 \wedge cdcl_W-merge-cp** T V
 \wedge conflicting V = None)
 \vee (cdcl_W-merge-cp** R V \wedge conflicting V = None)
 \vee (\exists U. cdcl_W-merge-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-s-R = this(4)

from s'

show ?case

proof cases

case conflict'

consider

(s') cdcl_W-merge-stgy** R V
| (dec-conf) S T U **where** cdcl_W-merge-stgy** R S **and** no-step cdcl_W-merge-cp S **and**
decide S T **and** cdcl_W-merge-cp** T U **and** conflict U V
| (dec) S T **where** cdcl_W-merge-stgy** R S **and** no-step cdcl_W-merge-cp S **and** decide S T
and cdcl_W-merge-cp** T V **and** conflicting V = None
| (cp) cdcl_W-merge-cp** R V
| (cp-conf) U **where** cdcl_W-merge-cp** R U **and** conflict U V

using IH **by** meson

then show ?thesis

proof cases

case s'

then have R = V **using** inv local.conflict' **unfolding** full1-def

by (metis trancpl-unfold-begin

rtrancpl-cdcl_W-merge-stgy'-no-step-cdcl_W-cp-or-eq)

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 trancpl-cdcl_W-cp-propagate-with-conflict-or-not[of V W] conflict'
unfolding full-unfold full1-def **by** meson

```

then show ?thesis
proof cases
  case V-W
  then show ?thesis using  $\langle R = V \rangle$  n-s-R by simp
next
  case propa
  then show ?thesis using  $\langle R = V \rangle$  by (auto intro: cdclW-merge-cp.intros)
next
  case propa-confl
  moreover
    then have cdclW-merge-cp** V V'
    by (metis rtranclp-unfold cdclW-merge-cp.propagate' r-into-rtranclp)
  ultimately show ?thesis using s'  $\langle R = V \rangle$  by blast
qed
next
  case dec-confl note - = this(5)
  then have False using conflict' unfolding full1-def by (auto dest!: tranclpD elim: rulesE)
  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-cdclW-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 cdclW-merge-cp.propagate' dec rtranclp.rtrancl-into-rtrancl)
next
  case propa-confl
  then have cdclW-merge-cp** T V'
    using T-V by (metis rtranclp-unfold cdclW-merge-cp.propagate' rtranclp.simps)
  then show ?thesis using dec propa-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-cdclW-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 cdclW-merge-cp.propagate' cp
    rtranclp.rtrancl-into-rtrancl)
next
  case propa-confl
  then show ?thesis
    using propa-confl(2) cp
    by (metis (full-types) cdclW-merge-cp.propagate' rtranclp.rtrancl-into-rtrancl
      rtranclp-unfold)
qed
next

```

```

    case cp-conflict
    then show ?thesis using conflict' unfolding full1-def by (fastforce dest!: tranclpD
      elim!: rulesE)
  qed
next
case (decide' V)
then have conf-V: conflicting V = None
  by (auto elim: rulesE)
consider
  (s') cdclW-merge-stgy** R V
| (dec-conflict) 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
| (cp-conflict) U where cdclW-merge-cp** R U and conflict U V
using IH by meson
then show ?thesis
proof cases
  case s'
  have conf-V': conflicting V' = None using decide'(1) by (auto elim: rulesE)
  have full: full1 cdclW-cp V' W  $\vee$  (V' = W  $\wedge$  no-step cdclW-cp W)
    using decide'(3) unfolding full-unfold by blast
  consider
    (V'-W) V' = W
  | (propa) propagate++ V' W and conflicting W = None
  | (propa-conflict) V'' where propagate** V' V'' and conflict V'' W
  using tranclp-cdclW-cp-propagate-with-conflict-or-not[of V W] decide'
    (full1 cdclW-cp V' W  $\vee$  V' = W  $\wedge$  no-step cdclW-cp W) unfolding full1-def
  by (metis tranclp-cdclW-cp-propagate-with-conflict-or-not)
  then show ?thesis
  proof cases
    case V'-W
    then show ?thesis
      using conf-V' local.decide'(1,2) s' conf-V
      no-step-cdclW-cp-no-step-cdclW-merge-restart[of V]
      by auto
  next
  case propa
  then show ?thesis using local.decide'(1,2) s' by (metis cdclW-merge-cp.simps conf-V
    no-step-cdclW-cp-no-step-cdclW-merge-restart r-into-rtranclp)
  next
  case propa-conflict
  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-conflict(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 elim: rulesE)
    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 (blast intro: cdclW-merge-cp.intros)
    ultimately show ?thesis
      using ⟨cdclW-merge-stgy** R V⟩ decide' ⟨no-step cdclW-merge-cp V⟩
      by (meson r-into-rtranclp)
  next
    case propa-conf
    moreover then have cdclW-merge-cp** V' V''
      by (metis cdclW-merge-cp.propagate' rtranclp-unfold tranclp-unfold-end)
    ultimately show ?thesis using ⟨cdclW-merge-stgy** R V⟩ decide'
      ⟨no-step cdclW-merge-cp V⟩ by (meson r-into-rtranclp)
  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 auto
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-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 elim: rulesE)
  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 (blast intro: cdclW-merge-cp.intros)
ultimately show ?thesis using ⟨cdclW-merge-stgy** R V⟩ decide'
  ⟨no-step cdclW-merge-cp V⟩ by (meson r-into-rtrancp)
next
case propa-confl
moreover then have cdclW-merge-cp** V' V''
  by (metis cdclW-merge-cp.propagate' rtrancp-unfold trancp-unfold-end)
ultimately show ?thesis using ⟨cdclW-merge-stgy** R V⟩ decide'
  ⟨no-step cdclW-merge-cp V⟩ by (meson r-into-rtrancp)
qed
next
case (dec-confl)
show ?thesis using conf-V dec-confl(5) by (auto elim!: rulesE
  simp del: state-simp simp: state-eq-def)
next
case cp-confl
then show ?thesis using decide' apply - by (intro HOL.disjI2) (fastforce elim: rulesE
  simp del: state-simp simp: state-eq-def)
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-confl) S T U where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and
  decide S T and cdclW-merge-cp** T U and conflict U V
| (dec) S T where cdclW-merge-stgy** R S and no-step cdclW-merge-cp S and decide S T
  and cdclW-merge-cp** T V and conflicting V = None
| (cp) cdclW-merge-cp** R V and conflicting V = None
| (cp-confl) U where cdclW-merge-cp** R U and conflict U V
using IH by meson
then show ?thesis
proof cases
case s' note - = this(2)
then have False
  using bj'(1) unfolding full1-def by (force dest!: trancpD simp: cdclW-bj.simps
    elim: rulesE)
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
    elim: rulesE)
then show ?thesis by fast
next
case dec-confl
then have cdclW-merge-cp U V'
  using bj' cdclW-merge-cp.intros(1)[of U V V'] by (simp add: full-unfold)
then have cdclW-merge-cp** T V'
  using dec-confl(4) by simp
consider

```

```

  (V'-W) V' = W
| (propa) propagate++ V' W and conflicting W = 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'(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 tranclpD
      no-step-cdclW-cp-no-conflict-no-propagate(1) )
then have full1 cdclW-merge-cp T V'
  unfolding full1-def using ⟨cdclW-merge-cp U V'⟩ dec-confl(4) by auto
then have full cdclW-merge-cp T V'
  by (simp add: full-unfold)
then have cdclW-merge-stgy S V'
  using dec-confl(3) cdclW-merge-stgy.fw-s-decide ⟨no-step cdclW-merge-cp S⟩ by blast
then have cdclW-merge-stgy** R V'
  using ⟨cdclW-merge-stgy** R S⟩ by auto
show ?thesis
proof cases
assume conflicting W = 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'⟩
      conflictE conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj
      dec-confl(5) r-into-rtranclp)
qed
next
case propa
moreover then have cdclW-merge-cp V' W by (blast intro: cdclW-merge-cp.intros)
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-conf(1) by force
    next
      assume confl: conflicting V' ≠ 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 elim: rulesE)
      have no-step cdclW-merge-cp V'
      using confl by (auto simp: full1-def full-def cdclW-merge-cp.simps
        dest!: tranclpD elim: rulesE)
      moreover have cdclW-merge-cp U W
      using V'-W ⟨cdclW-merge-cp U V'⟩ by blast
      ultimately have full1 cdclW-merge-cp R V'
      using cp-conf(1) V'-W unfolding full1-def by auto
      then have cdclW-merge-stgy R V'
      by auto
      moreover have no-step cdclW-merge-stgy V'
      using confl ⟨no-step cdclW-merge-cp V'⟩ by (auto simp: cdclW-merge-stgy.simps
        full1-def dest!: tranclpD elim: rulesE)
      ultimately have cdclW-merge-stgy** R V' by auto
      { fix ss :: 'st
        have cdclW-merge-cp U W
        using V'-W ⟨cdclW-merge-cp U V'⟩ by blast
        then have ¬ cdclW-bj W ss
        by (meson conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj
          cp-conf(1) rtranclp.rtrancl-into-rtrancl step.prem)
        then have cdclW-merge-stgy** R W ∧ conflicting W = None ∨
          cdclW-merge-stgy** R W ∧ ¬ cdclW-bj W ss
        using V'-W ⟨cdclW-merge-stgy** R V'⟩ by presburger }
      then show ?thesis
      by presburger
    qed
  next
    case propa
    moreover then have cdclW-merge-cp V' W
    by (blast intro: cdclW-merge-cp.intros)
    ultimately show ?thesis using ⟨cdclW-merge-cp U V'⟩ cp-conf(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 ⟨cdclW-merge-cp U V'⟩ cp-conf(1) by (metis rtranclp.rtrancl-into-rtrancl
      rtranclp-trans)
  qed
qed
qed
qed

```

```

lemma decide-rtrancpl-cdclW-s'-rtrancpl-cdclW-s':
  assumes
    dec: decide S T and
    cdclW-s'** T U and
    n-s-S: no-step cdclW-cp S and
    no-step cdclW-cp U
  shows cdclW-s'** S U
  using assms(2,4)
proof induction
  case (step U V) note st = this(1) and s' = this(2) and IH = this(3) and n-s = this(4)
  consider
    (TU) T = U
  | (s'-st) T' where cdclW-s' T T' and cdclW-s'** T' U
  using st[unfolded rtrancpl-unfold] by (auto dest!: trancplD)
then show ?case
proof cases
  case TU
  then show ?thesis
  proof –
    assume a1: T = U
    then have f2: cdclW-s' T V
    using s' by force
    obtain ss :: 'st where
      ss: cdclW-s'** S T ∨ cdclW-cp T ss
    using a1 step.IH by blast–
    obtain ssa :: 'st ⇒ 'st where
      f3: ∀ s sa sb. (¬ decide s sa ∨ cdclW-cp s (ssa s) ∨ ¬ full cdclW-cp sa sb)
      ∨ cdclW-s' s sb
    using cdclW-s'.decide' by moura
    have ∀ s sa. ¬ cdclW-s' s sa ∨ full1 cdclW-cp s sa ∨
      (∃ sb. decide s sb ∧ no-step cdclW-cp s ∧ full cdclW-cp sb sa) ∨
      (∃ sb. full1 cdclW-bj s sb ∧ no-step cdclW-cp s ∧ full cdclW-cp sb sa)
    by (metis cdclW-s'E)
    then have ∃ s. cdclW-s'** S s ∧ cdclW-s' s V
    using f3 ss f2 by (metis dec full1-is-full n-s-S rtrancpl-unfold)
    then show ?thesis
    by force
  qed
next
  case (s'-st T') note s'-T' = this(1) and st = this(2)
  have cdclW-s'** S T'
  using s'-T'
  proof cases
  case conflict'
  then have cdclW-s' S T'
    using dec cdclW-s'.decide' n-s-S by (simp add: full-unfold)
  then show ?thesis
    using st by auto
  next
  case (decide' T'')
  then have cdclW-s' S T
    using dec cdclW-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!: tranclpD simp: cdclW-bj.simps
        elim: rulesE)
    then show ?thesis by fast
  qed
  then show ?thesis using s' st by auto
qed
next
case base
then have full cdclW-cp T T
  by (simp add: full-unfold)
then show ?case
  using cdclW-s'.simps dec n-s-S by auto
qed

lemma rtranclp-cdclW-merge-stgy-rtranclp-cdclW-s':
  assumes
    cdclW-merge-stgy** R V and
    inv: cdclW-all-struct-inv R
  shows cdclW-s'** R V
  using assms(1)
proof induction
  case base
  then show ?case by simp
next
case (step S T) note st = this(1) and fw = this(2) and IH = this(3)
have cdclW-all-struct-inv S
  using inv 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
  have  $\bigwedge s. \neg \text{full } cdcl_W\text{-merge-cp } s \ S$ 
    using fw-s-cp unfolding full-def full1-def by (metis tranclp-unfold-begin)
  then have S = R
    using fw-s-cp unfolding full1-def by (metis cdclW-cp.conflict' cdclW-cp.propagate'
      cdclW-merge-cp.cases tranclp-unfold-begin inv st
      rtranclp-cdclW-merge-stgy'-no-step-cdclW-cp-or-eq)
  then have full1 cdclW-s'-without-decide R T
    using inv local.fw-s-cp
    by (blast intro: conflicting-true-full1-cdclW-merge-cp-imp-full1-cdclW-s'-without-decode)
  then show ?thesis unfolding full1-def
    by (metis (no-types) rtranclp-cdclW-s'-without-decide-rtranclp-cdclW-s' rtranclp-unfold)
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 elim: rulesE)
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
      rtrancpl-cdclW-merge-stgy'-no-step-cdclW-cp-or-eq)
    then show ?thesis using IH by auto
  qed
qed

lemma rtrancpl-cdclW-merge-stgy-distinct-mset-clauses:
  assumes invR: cdclW-all-struct-inv R and
  st: cdclW-merge-stgy** R S and
  dist: distinct-mset (clauses R) and
  R: trail R = []
  shows distinct-mset (clauses S)
  using rtrancpl-cdclW-stgy-distinct-mset-clauses[OF invR - dist R]
  invR st rtrancpl-mono[of cdclW-s' cdclW-stgy**] cdclW-s'-is-rtrancpl-cdclW-stgy
  by (auto dest!: cdclW-s'-is-rtrancpl-cdclW-stgy rtrancpl-cdclW-merge-stgy-rtrancpl-cdclW-s')

lemma no-step-cdclW-s'-no-step-cdclW-merge-stgy:
  assumes
    inv: cdclW-all-struct-inv R and s': no-step cdclW-s' R
  shows no-step cdclW-merge-stgy R
proof -
  { fix ss :: 'st
    obtain ssa :: 'st ⇒ 'st ⇒ 'st where
      ff1:  $\bigwedge s sa. \neg \text{cdcl}_W\text{-merge-stgy } s sa \vee \text{full1 } \text{cdcl}_W\text{-merge-cp } s sa \vee \text{decide } s (ssa s sa)$ 
      using cdclW-merge-stgy.cases by moura
    obtain ssb :: ('st ⇒ 'st ⇒ bool) ⇒ 'st ⇒ 'st ⇒ 'st where
      ff2:  $\bigwedge p s sa. \neg p^{++} s sa \vee p s (ssb p s sa)$ 
      by (meson trancpl-unfold-begin)
    obtain ssc :: 'st ⇒ 'st where
      ff3:  $\bigwedge s sa sb. (\neg \text{cdcl}_W\text{-all-struct-inv } s \vee \neg \text{cdcl}_W\text{-cp } s sa \vee \text{cdcl}_W\text{-s' } s (ssc s))$ 
       $\wedge (\neg \text{cdcl}_W\text{-all-struct-inv } s \vee \neg \text{cdcl}_W\text{-o } s sb \vee \text{cdcl}_W\text{-s' } s (ssc s))$ 
      using n-step-cdclW-stgy-iff-no-step-cdclW-cl-cdclW-o by moura
    then have ff4:  $\bigwedge s. \neg \text{cdcl}_W\text{-o } R s$ 
      using s' inv by blast
    have ff5:  $\bigwedge s. \neg \text{cdcl}_W\text{-cp}^{++} R s$ 
      using ff3 ff2 s' by (metis inv)
    have  $\bigwedge s. \neg \text{cdcl}_W\text{-bj}^{++} R s$ 
      using ff4 ff2 by (metis bj)
    then have  $\bigwedge s. \neg \text{cdcl}_W\text{-s' -without-decide } R s$ 
      using ff5 by (simp add: cdclW-s'-without-decide.simps full1-def)
    then have  $\neg \text{cdcl}_W\text{-s' -without-decide}^{++} R ss$ 
      using ff2 by blast
    then have  $\neg \text{full1 } \text{cdcl}_W\text{-s' -without-decide } R ss$ 
      by (simp add: full1-def)
    then have  $\neg \text{cdcl}_W\text{-merge-stgy } R ss$ 
      using ff4 ff1 conflicting-true-full1-cdclW-merge-cp-imp-full1-cdclW-s'-without-decode inv
      by blast }
  then show ?thesis
    by fastforce
  qed
end

```

Termination and full Equivalence

We will discharge the assumption later using NOT's proof of termination.

```

locale conflict-driven-clause-learningW-termination =
  conflict-driven-clause-learningW +
  assumes wf-cdclW-merge-inv: wf  $\{(T, S). \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge } S \ T\}$ 
begin

lemma wf-tranclp-cdclW-merge: wf  $\{(T, S). \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge}^{++} S \ T\}$ 
  using wf-trancl[OF wf-cdclW-merge-inv]
  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 wf-cdclW-merge-cp:
  wf  $\{(T, S). \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-cp } S \ T\}$ 
  using wf-tranclp-cdclW-merge by (rule wf-subset) (auto simp: cdclW-merge-cp-tranclp-cdclW-merge)

lemma wf-cdclW-merge-stgy:
  wf  $\{(T, S). \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-stgy } S \ T\}$ 
  using wf-tranclp-cdclW-merge by (rule wf-subset)
  (auto simp add: cdclW-merge-stgy-tranclp-cdclW-merge)

lemma cdclW-merge-cp-obtain-normal-form:
  assumes inv: cdclW-all-struct-inv R
  obtains S where full cdclW-merge-cp R S
proof –
  obtain S where full  $(\lambda S \ T. \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-cp } S \ T) \ R \ S$ 
  using wf-exists-normal-form-full[OF wf-cdclW-merge-cp] by blast
  then have
    st:  $(\lambda S \ T. \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-cp } S \ T)^{**} \ R \ S$  and
    n-s: no-step  $(\lambda S \ T. \text{cdcl}_W\text{-all-struct-inv } S \wedge \text{cdcl}_W\text{-merge-cp } S \ T) \ S$ 
  unfolding full-def by blast+
  have cdclW-merge-cp** R S
  using st by induction auto
  moreover
    have cdclW-all-struct-inv S
    using st inv
    apply (induction rule: rtranclp-induct)
    apply simp
    by (meson r-into-rtranclp rtranclp-cdclW-all-struct-inv-inv
      rtranclp-cdclW-merge-cp-rtranclp-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-cdclW-merge-stgy-no-step-cdclW-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  $\neg ?thesis$ 
  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'
  proof –
    obtain  $R'$  where
      cdclW-merge-cp R R'
    using inv unfolding cdclW-all-struct-inv-def by (meson confl
      cdclW-s'-without-decide.simps conflict'
      conflicting-true-no-step-cdclW-merge-cp-no-step-s'-without-decide)
    then show ?thesis
      using that by (metis cdclW-merge-cp-obtain-normal-form full-unfold inv)
    qed
  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 auto
qed
qed

```

```

lemma rtranclp-cdclW-merge-cp-no-step-cdclW-bj:
  assumes conflicting R = None and cdclW-merge-cp** R S
  shows no-step cdclW-bj S
  using assms conflicting-not-true-rtranclp-cdclW-merge-cp-no-step-cdclW-bj by auto

```

```

lemma rtranclp-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 elim: rulesE)
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!: tranclpD elim: rulesE)
from fw show ?case
proof cases
  case fw-s-cp
  then show ?thesis
    using rtranclp-cdclW-merge-cp-no-step-cdclW-bj confl-S
    by (simp add: full1-def tranclp-into-rtranclp)
next
case (fw-s-decide S')
moreover then have conflicting S' = None by (auto elim: rulesE)

```

```

    ultimately show ?thesis
    using conflicting-not-true-rtrancp-cdclW-merge-cp-no-step-cdclW-bj
    unfolding full-def by meson
qed
qed

end

end
theory CDCL-WNOT
imports CDCL-NOT CDCL-W-Termination CDCL-W-Merge
begin

```

6.3 Link between Weidenbach's and NOT's CDCL

6.3.1 Inclusion of the states

```

declare upt.simps(2)[simp del]

fun convert-ann-lit-from-W where
  convert-ann-lit-from-W (Propagated L -) = Propagated L () |
  convert-ann-lit-from-W (Decided L) = Decided L

abbreviation convert-trail-from-W ::
  ('v, 'mark) ann-lits
  ⇒ ('v, unit) ann-lits where
  convert-trail-from-W ≡ map convert-ann-lit-from-W

lemma lits-of-l-convert-trail-from-W[simp]:
  lits-of-l (convert-trail-from-W M) = lits-of-l M
  by (induction rule: ann-lit-list-induct) simp-all

lemma lit-of-convert-trail-from-W[simp]:
  lit-of (convert-ann-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) ⟷ no-dup M
  by (auto simp: comp-def)

lemma convert-trail-from-W-true-annots[simp]:
  convert-trail-from-W M ⊨as C ⟷ M ⊨as C
  by (auto simp: true-annots-true-cls image-image lits-of-def)

lemma defined-lit-convert-trail-from-W[simp]:
  defined-lit (convert-trail-from-W S) L ⟷ defined-lit S L
  by (auto simp: defined-lit-map image-comp)

```

The values 0 and $\{\#\}$ are dummy values.

```

consts dummy-cls :: 'cls
fun convert-ann-lit-from-NOT
  :: ('v, 'mark) ann-lit ⇒ ('v, 'cls) ann-lit where
  convert-ann-lit-from-NOT (Propagated L -) = Propagated L dummy-cls |
  convert-ann-lit-from-NOT (Decided L) = Decided L

```

abbreviation *convert-trail-from-NOT* **where**
convert-trail-from-NOT \equiv *map convert-ann-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: ann-lit-list-induct*) (*auto simp: defined-lit-map*)

lemma *lits-of-l-convert-trail-from-NOT*:
lits-of-l (convert-trail-from-NOT F) = lits-of-l F
by (*induction F rule: ann-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: ann-lit-list-induct*) *auto*

lemma *convert-trail-from-W-convert-lit-from-NOT*[*simp*]:
convert-ann-lit-from-W (convert-ann-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-ann-lit-from-NOT*[*iff*]:
lit-of (convert-ann-lit-from-NOT L) = lit-of L
by (*cases L*) *auto*

sublocale *state_W* \subseteq *dpLL-state-ops*
 $\lambda S.$ *convert-trail-from-W (trail S)*
clauses
 $\lambda L S.$ *cons-trail (convert-ann-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*
by *unfold-locales*

sublocale *state_W* \subseteq *dpLL-state*
 $\lambda S.$ *convert-trail-from-W (trail S)*
clauses
 $\lambda L S.$ *cons-trail (convert-ann-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*
by *unfold-locales (auto simp: map-tl o-def)*

context *state_W*
begin
declare *state-simp_{NOT}*[*simp del*]
end

sublocale *conflict-driven-clause-learning_W* \subseteq *cdcl_{NOT}-merge-bj-learn-ops*
 $\lambda S.$ *convert-trail-from-W (trail S)*
clauses

```

λL S. cons-trail (convert-ann-lit-from-NOT L) S
λS. tl-trail S
λC S. add-learned-cls C S
λC S. remove-cls C S
λ- -. True
λ- S. conflicting S = None
λC C' L' S T. backjump-l-cond C C' L' S T
  ∧ distinct-mset (C' + {#L'#}) ∧ ¬tautology (C' + {#L'#})
by unfold-locales

thm cdclNOT-merge-bj-learn-proxy.axioms
sublocale conflict-driven-clause-learningW ⊆ cdclNOT-merge-bj-learn-proxy
λS. convert-trail-from-W (trail S)
  clauses
λL S. cons-trail (convert-ann-lit-from-NOT L) S
λS. tl-trail S
λC S. add-learned-cls C S
λC S. remove-cls C S

λ- -. True
λ- S. conflicting S = None
backjump-l-cond
invNOT
proof (unfold-locales, goal-cases)
  case 2
  then show ?case using cdclNOT-merged-bj-learn-no-dup-inv by (auto simp: comp-def)
next
case (1 C' S C F' K F L)
moreover
  let ?C' = remdups-mset C'
  have L ∉ # C'
    using ⟨F ⊨as CNot C'⟩ ⟨undefined-lit F L⟩ Decided-Propagated-in-iff-in-lits-of-l
    in-CNot-implies-uminus(2) by fast
  then have distinct-mset (?C' + {#L'#})
    by (simp add: distinct-mset-single-add)
moreover
  have no-dup F
    using ⟨invNOT S⟩ ⟨convert-trail-from-W (trail S) = F' @ Decided K # F⟩
    unfolding invNOT-def
    by (smt comp-apply distinct.simps(2) distinct-append list.simps(9) map-append
      no-dup-convert-from-W)
  then have consistent-interp (lits-of-l F)
    using distinct-consistent-interp by blast
  then have ¬ tautology C'
    using ⟨F ⊨as CNot C'⟩ consistent-CNot-not-tautology true-annots-true-cls by blast
  then have ¬ tautology (?C' + {#L'#})
    using ⟨F ⊨as CNot C'⟩ ⟨undefined-lit F L⟩ by (metis CNot-remdups-mset
      Decided-Propagated-in-iff-in-lits-of-l add.commute in-CNot-uminus tautology-add-single
      tautology-remdups-mset true-annot-singleton true-annots-def)
show ?case
proof -
  have f2: no-dup (convert-trail-from-W (trail S))
    using ⟨invNOT S⟩ unfolding invNOT-def by (simp add: o-def)
  have f3: atm-of L ∈ atms-of-mm (clauses S)
    ∪ atm-of ' lits-of-l (convert-trail-from-W (trail S))
    using ⟨convert-trail-from-W (trail S) = F' @ Decided K # F⟩

```

```

  ⟨atm-of L ∈ atms-of-mm (clauses S) ∪ atm-of ‘ lits-of-l (F' @ Decided 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-clss-remdups-mset union-commute)
have F ⊨as CNot (remdups-mset C')
  by (simp add: ⟨F ⊨as CNot C'⟩)
have Ex (backjump-l S)
  apply standard
  apply (rule backjump-l.intros[OF - f2, of - - ])
  using f4 f3 f2 ⟨¬ tautology (remdups-mset C' + {#L#})⟩
    calculation(2-5,9) ⟨F ⊨as CNot (remdups-mset C')⟩
    state-eqNOT-ref unfolding backjump-l-cond-def by blast+
then show ?thesis
  by blast
qed
qed

```

```

sublocale conflict-driven-clause-learningW ⊆ cdclNOT-merge-bj-learn-proxy2
  λS. convert-trail-from-W (trail S)
  clauses
  λL S. cons-trail (convert-ann-lit-from-NOT L) S
  λS. tl-trail S
  λC S. add-learned-cls C S
  λC S. remove-cls C S
  λ-. True
  λ-. S. conflicting S = None backjump-l-cond invNOT
by unfold-locales

```

```

sublocale conflict-driven-clause-learningW ⊆ cdclNOT-merge-bj-learn
  λS. convert-trail-from-W (trail S)
  clauses
  λL S. cons-trail (convert-ann-lit-from-NOT L) S
  λS. tl-trail S
  λC S. add-learned-cls C S
  λC S. remove-cls C S
  backjump-l-cond
  λ-. True
  λ-. S. conflicting S = None invNOT
apply unfold-locales
  using dpll-bj-no-dup apply (simp add: comp-def)
using cdclNOT.simps cdclNOT-no-dup no-dup-convert-from-W unfolding invNOT-def by blast

```

```

context conflict-driven-clause-learningW
begin

```

Notations are lost while proving locale inclusion:

```

notation state-eqNOT (infix ~NOT 50)

```

6.3.2 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.elim)
qed

lemma trail-reduce-trail-toNOT-add-learned-cl:
no-dup (trail S) ⇒
  trail (reduce-trail-toNOT M (add-learned-cl D S)) = trail (reduce-trail-toNOT M S)
by (rule trailW-eq-reduce-trail-toNOT-eq) simp

lemma reduce-trail-toNOT-reduce-trail-convert:
  reduce-trail-toNOT C S = reduce-trail-to (convert-trail-from-NOT C) S
  apply (induction C S rule: reduce-trail-toNOT.induct)
  apply (subst reduce-trail-toNOT.simps, subst reduce-trail-to.simps)
  by auto

lemma reduce-trail-to-map[simp]:
  reduce-trail-to (map f M) S = reduce-trail-to M S
  by (rule reduce-trail-to-length) simp

lemma reduce-trail-toNOT-map[simp]:
  reduce-trail-toNOT (map f M) S = reduce-trail-toNOT M S
  by (rule reduce-trail-toNOT-length) simp

lemma skip-or-resolve-state-change:
  assumes skip-or-resolve** S T
  shows
    ∃ M. trail S = M @ trail T ∧ (∀ m ∈ set M. ¬is-decided m)
    clauses S = clauses T
    backtrack-lvl S = backtrack-lvl T
  using assms
proof (induction rule: rtrancpl-induct)
  case base
  case 1 show ?case by simp
  case 2 show ?case by simp
  case 3 show ?case by simp
next
  case (step T U) note st = this(1) and s-o-r = this(2) and IH = this(3) and IH' = this(3-5)

  case 2 show ?case using IH' s-o-r by (auto elim!: rulesE simp: skip-or-resolve.simps)
  case 3 show ?case using IH' s-o-r by (auto elim!: rulesE simp: skip-or-resolve.simps)
  case 1 show ?case
    using s-o-r
  proof cases
    case s-or-r-skip
    then show ?thesis using IH by (auto elim!: rulesE simp: skip-or-resolve.simps)
  next
    case s-or-r-resolve
    then show ?thesis
      using IH by (cases trail T) (auto elim!: rulesE simp: skip-or-resolve.simps)
  qed
qed

```

6.3.3 Inclusion of Weidenbach's CDCL in NOT's CDCL

This lemma shows the inclusion of Weidenbach's CDCL *cdcl_W-merge* (with merging) in NOT's *cdcl_{NOT}-merged-bj-learn*.

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 (*no-step cdcl_W-merge T* \wedge *conflicting T* \neq *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: *state T = (Propagated L (C + {#L#}) # M, N, U, k, None)*

by (*auto elim: propagate-high-levelE*)

have *propagate_{NOT} S T*

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-mm (init-clss S)* **and**

T: *T ∼ cons-trail (Decided L)*

(*update-backtrack-lvl (Suc (backtrack-lvl S)) S*)

by (*auto elim: decideE*)

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

case (*fw-forget S T*) **note** *rf = this(1)* **and** *inv = this(2)*

then obtain *C* **where**

S: *conflicting S = None* **and**

C-le: *C ∈ # learned-clss S* **and**

\neg (*trail S*) \models_{asm} *clauses S* **and**

C \notin *set (get-all-mark-of-propagated (trail S))* **and**

C-init: *C* \notin *# init-clss S* **and**

T: *T ∼ remove-cls C S*

by (*auto elim: forgetE*)

have *init-clss S ⊨_{pm} C*

using *inv C-le* **unfolding** *cdcl_W-all-struct-inv-def cdcl_W-learned-clause-def clauses-def*

by (*meson true-clss-clss-in-imp-true-clss-cls*)

then have *S-C*: *removeAll-mset C (clauses S) ⊨_{pm} C*

using *C-init C-le* **unfolding** *clauses-def* **by** (*auto simp add: Un-Diff ac-simps*)

```

have forgetNOT S T
  apply (rule forgetNOT.forgetNOT)
    using S-C apply blast
    using S apply simp
    using C-init C-le 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
    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 CT where
  confl-T: conflicting T = Some CT and
  CT: CT = CS and
  CS: CS ∈ # clauses S and
  tr-S-CS: trail S ⊨as CNot CS
  using confl by (elim conflictE) (auto simp del: state-simp simp: state-eq-def)
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 ≠ None
    using confl by (induction rule: rtrancpl-induct)
    (auto simp del: state-simp simp: skip-or-resolve.simps state-eq-def elim!: rulesE)
  moreover then have no-step cdclW-merge U
    by (auto simp: cdclW-merge.simps elim: rulesE)
  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
  by blast
then have cdclW-M-level-inv T'
  using rtrancpl-cdclW-consistent-inv (cdclW-M-level-inv T) by blast
then obtain M1 M2 i D L K where
  confl-T': conflicting T' = Some D and
  LD: L ∈ # D and
  M1-M2: (Decided K # M1, M2) ∈ set (get-all-ann-decomposition (trail T')) and
  get-level (trail T') K = i+1
  get-level (trail T') L = backtrack-lvl T' and
  get-level (trail T') L = get-maximum-level (trail T') D and
  get-maximum-level (trail T') (remove1-mset L D) = i and
  U: U ∼ cons-trail (Propagated L D)
  (reduce-trail-to M1
    (add-learned-cls D
      (update-backtrack-lvl i
        (update-conflicting None T')))))
  using bt by (auto elim: backtrackE)
have [simp]: clauses S = clauses T

```

```

    using confl by (auto elim: rulesE)
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 simp: skip-or-resolve.simps elim: rulesE)
      then show ?case using IH by auto
    qed
have inv-T: cdclW-all-struct-inv T
  by (meson cdclW-cp.simps confl inv r-into-rtranclp rtranclp-cdclW-all-struct-inv-inv
    rtranclp-cdclW-cp-rtranclp-cdclW)
have cdclW** T T'
  using rtranclp-skip-or-resolve-rtranclp-cdclW s-or-r by blast
have inv-T': cdclW-all-struct-inv T'
  using cdclW** T T' inv-T rtranclp-cdclW-all-struct-inv-inv by blast
have inv-U: cdclW-all-struct-inv U
  using cdclW-merge-restart-cdclW confl fw-r-conflict inv local.bj
    rtranclp-cdclW-all-struct-inv-inv by blast

have [simp]: init-clss S = init-clss T'
  using cdclW** T T' cdclW-init-clss confl cdclW-all-struct-inv-def conflict inv
    by (metis cdclW-M-level-inv T) rtranclp-cdclW-init-clss)
then have atm-L: atm-of L ∈ atms-of-mm (clauses S)
  using inv-T' confl-T' LD unfolding cdclW-all-struct-inv-def no-strange-atm-def
    clauses-def
    by (simp add: atms-of-def image-subset-iff)
obtain M where tr-T: trail T = M @ trail T'
  using s-or-r skip-or-resolve-state-change by meson
obtain M' where
  tr-T': trail T' = M' @ Decided K # tl (trail U) and
  tr-U: trail U = Propagated L D # tl (trail U)
  using U M1-M2 inv-T' unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def
    by fastforce
def M'' ≡ M @ M'
have tr-T: trail S = M'' @ Decided K # tl (trail U)
  using tr-T tr-T' confl unfolding M''-def by (auto elim: rulesE)
have init-clss T' + learned-clss S ⊨pm D
  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 @ [Decided K]])
  using confl M1-M2 trail T = M @ trail T'
  apply (auto dest!: get-all-ann-decomposition-exists-prepend
    elim!: conflE)
  by (rule sym) auto
ultimately have [simp]: trail (reduce-trail-toNOT M1 S) = M1
  using M1-M2 confl by (subst reduce-trail-toNOT-reduce-trail-convert)
    (auto simp: comp-def elim: rulesE)
have every-mark-is-a-conflict U

```

```

    using inv-U unfolding cdclW-all-struct-inv-def cdclW-conflicting-def by simp
  then have U-D: tl (trail U)  $\models_{as}$  CNot (remove1-mset L D)
    by (metis append-self-conv2 tr-U)
  have undef-L: undefined-lit (tl (trail U)) L
    using U M1-M2 inv-U unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def
    by (auto simp: lits-of-def defined-lit-map)
  have backjump-l S U
    apply (rule backjump-l[of - - - - L D - remove1-mset L D])
      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 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 auto[]
    using tr-S-CS apply simp

    using undef-L apply auto[]
    using atm-L apply (simp add: trail-reduce-trail-toNOT-add-learned-cls)
    using (init-cls T' + learned-cls S  $\models_{pm}$  D) LD unfolding clauses-def
    apply simp
    using LD apply simp
  apply (metis U-D convert-trail-from-W-true-annots)
  using inv-T' inv-U U confl-T' undef-L M1-M2 LD 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

```

abbreviation $cdcl_{NOT}\text{-restart}$ **where**

$cdcl_{NOT}\text{-restart} \equiv restart\text{-ops}.cdcl_{NOT}\text{-raw-restart } cdcl_{NOT} \text{ restart}$

lemma $cdcl_W\text{-merge-restart-is-cdcl}_{NOT}\text{-merged-bj-learn-restart-no-step}$:

assumes

inv : $cdcl_W\text{-all-struct-inv } S$ **and**

$cdcl_W$: $cdcl_W\text{-merge-restart } S \ T$

shows $cdcl_{NOT}\text{-restart}^{**} S \ T \vee (no\text{-step } cdcl_W\text{-merge } T \wedge conflicting \ T \neq None)$

proof –

consider

(fw) $cdcl_W\text{-merge } S \ T$

| (fw-r) $restart \ S \ T$

using $cdcl_W$ **by** (meson $cdcl_W\text{-merge-restart.simps } cdcl_W\text{-rf.cases fw-conflict fw-decide fw-forget}$
fw-propagate)

then show ?thesis

proof cases

case fw

then have IH: $cdcl_{NOT}\text{-merged-bj-learn } S \ T \vee (no\text{-step } cdcl_W\text{-merge } T \wedge conflicting \ T \neq None)$

using inv $cdcl_W\text{-merge-is-cdcl}_{NOT}\text{-merged-bj-learn}$ **by** blast

have $invS$: $inv_{NOT} \ S$

using inv **unfolding** $cdcl_W\text{-all-struct-inv-def } cdcl_W\text{-M-level-inv-def}$ **by** auto

have ff2: $cdcl_{NOT}^{++} S \ T \longrightarrow cdcl_{NOT}^{**} S \ T$

by (meson tranclp-into-rtranclp)

have ff3: $no\text{-dup } (convert\text{-trail-from-} W \ (trail \ S))$

using $invS$ **by** (simp add: comp-def)

have $cdcl_{NOT} \leq cdcl_{NOT}\text{-restart}$

by (auto simp: restart-ops.cdcl_{NOT}-raw-restart.simps)

```

    then show ?thesis
      using ff3 ff2 IH cdclNOT-merged-bj-learn-is-tranclp-cdclNOT
      rtranclp-mono[of cdclNOT cdclNOT-restart] invS predicate2D by blast
  next
    case fw-r
    then show ?thesis by (blast intro: restart-ops.cdclNOT-raw-restart.intros)
  qed
qed

abbreviation  $\mu_{FW} :: 'st \Rightarrow nat$  where
 $\mu_{FW} S \equiv (if\ no\_step\ cdcl_W\text{-merge}\ S\ then\ 0\ else\ 1 + \mu_{CDCL}'\text{-merged}\ (set\ mset\ (init\ clss\ S))\ S)$ 

lemma cdclW-merge- $\mu_{FW}$ -decreasing:
assumes
  inv: cdclW-all-struct-inv S and
  fw: cdclW-merge S T
shows  $\mu_{FW} T < \mu_{FW} S$ 
proof -
  let ?A = init-clss S
  have atm-clauses: atms-of-mm (clauses S)  $\subseteq$  atms-of-mm ?A
    using inv unfolding cdclW-all-struct-inv-def no-strange-atm-def clauses-def by auto
  have atm-trail: atm-of ' lits-of-l (trail S)  $\subseteq$  atms-of-mm ?A
    using inv unfolding cdclW-all-struct-inv-def no-strange-atm-def clauses-def by auto
  have n-d: no-dup (trail S)
    using inv unfolding cdclW-all-struct-inv-def by (auto simp: cdclW-M-level-inv-decomp)
  have [simp]:  $\neg no\_step\ cdcl_W\text{-merge}\ S$ 
    using fw by auto
  have [simp]: init-clss S = init-clss T
    using cdclW-merge-restart-cdclW[of S T] inv rtranclp-cdclW-init-clss
    unfolding cdclW-all-struct-inv-def
    by (meson cdclW-merge.simps cdclW-merge-restart.simps cdclW-rf.simps fw)
  consider
    (merged) cdclNOT-merged-bj-learn S T
    | (n-s) no-step cdclW-merge T
    using cdclW-merge-is-cdclNOT-merged-bj-learn inv fw by blast
  then show ?thesis
  proof cases
    case merged
    then show ?thesis
      using cdclNOT-decreasing-measure'[OF - - atm-clauses, of T] atm-trail n-d
      by (auto split: if-split simp: comp-def image-image lits-of-def)
    next
    case n-s
    then show ?thesis by simp
  qed
qed

lemma wf-cdclW-merge: wf {(T, S). cdclW-all-struct-inv S  $\wedge$  cdclW-merge S T}
apply (rule wfP-if-measure[of - -  $\mu_{FW}$ ])
using cdclW-merge- $\mu_{FW}$ -decreasing by blast

sublocale conflict-driven-clause-learningW-termination
by unfold-locales (simp add: wf-cdclW-merge)

```

6.3.4 Correctness of $cdcl_W$ -merge-stgy

lemma $full\text{-}cdcl_W\text{-}s'\text{-}full\text{-}cdcl_W\text{-}merge\text{-}restart$:

assumes

$conflicting\ R = None$ **and**

$inv: cdcl_W\text{-}all\text{-}struct\text{-}inv\ R$

shows $full\ cdcl_W\text{-}s'\ R\ V \longleftrightarrow full\ cdcl_W\text{-}merge\text{-}stgy\ R\ V$ (**is** $?s' \longleftrightarrow ?fw$)

proof

assume $?s'$

then have $cdcl_W\text{-}s'^{**}\ R\ V$ **unfolding** $full\text{-}def$ **by** $blast$

have $cdcl_W\text{-}all\text{-}struct\text{-}inv\ V$

using $\langle cdcl_W\text{-}s'^{**}\ R\ V \rangle\ inv\ rtranclp\text{-}cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}inv\ rtranclp\text{-}cdcl_W\text{-}s'\text{-}rtranclp\text{-}cdcl_W$
by $blast$

then have $n\text{-}s: no\text{-}step\ cdcl_W\text{-}merge\text{-}stgy\ V$

using $no\text{-}step\text{-}cdcl_W\text{-}s'\text{-}no\text{-}step\text{-}cdcl_W\text{-}merge\text{-}stgy$ **by** ($meson\ \langle full\ cdcl_W\text{-}s'\ R\ V \rangle\ full\text{-}def$)

have $n\text{-}s\text{-}bj: no\text{-}step\ cdcl_W\text{-}bj\ V$

by ($metis\ \langle cdcl_W\text{-}all\text{-}struct\text{-}inv\ V \rangle\ \langle full\ cdcl_W\text{-}s'\ R\ V \rangle\ bj\ full\text{-}def$

$n\text{-}step\text{-}cdcl_W\text{-}stgy\text{-}iff\text{-}no\text{-}step\text{-}cdcl_W\text{-}cl\text{-}cdcl_W\text{-}o$)

have $n\text{-}s\text{-}cp: no\text{-}step\ cdcl_W\text{-}merge\text{-}cp\ V$

proof —

{ **fix** $ss :: 'st$

obtain $ssa :: 'st \Rightarrow 'st$ **where**

$ff1: \forall s. \neg cdcl_W\text{-}all\text{-}struct\text{-}inv\ s \vee cdcl_W\text{-}s'\text{-}without\text{-}decide\ s\ (ssa\ s)$
 $\vee no\text{-}step\ cdcl_W\text{-}merge\text{-}cp\ s$

using $conflicting\text{-}true\text{-}no\text{-}step\text{-}s'\text{-}without\text{-}decide\text{-}no\text{-}step\text{-}cdcl_W\text{-}merge\text{-}cp$ **by** $moura$

have $\forall p\ s\ sa. \neg full\ p\ (s::'st)\ sa \vee p^{**}\ s\ sa \wedge no\text{-}step\ p\ sa$ **and**

$\forall p\ s\ sa. (\neg p^{**}\ (s::'st)\ sa \vee (\exists s. p\ sa\ s)) \vee full\ p\ s\ sa$

by ($meson\ full\text{-}def$)+

then have $\neg cdcl_W\text{-}merge\text{-}cp\ V\ ss$

using $ff1$ **by** ($metis\ (no\text{-}types)\ \langle cdcl_W\text{-}all\text{-}struct\text{-}inv\ V \rangle\ \langle full\ cdcl_W\text{-}s'\ R\ V \rangle\ cdcl_W\text{-}s'\text{-}simps$
 $cdcl_W\text{-}s'\text{-}without\text{-}decide\text{-}cases$) }

then show $?thesis$

by $blast$

qed

consider

$(fw\text{-}no\text{-}confl)\ cdcl_W\text{-}merge\text{-}stgy^{**}\ R\ V$ **and** $conflicting\ V = None$

| $(fw\text{-}confl)\ cdcl_W\text{-}merge\text{-}stgy^{**}\ R\ V$ **and** $conflicting\ V \neq None$ **and** $no\text{-}step\ cdcl_W\text{-}bj\ V$

| $(fw\text{-}dec\text{-}confl)\ S\ T\ U$ **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** $conflict\ U\ V$

| $(fw\text{-}dec\text{-}no\text{-}confl)\ S\ T$ **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** $conflicting\ V = None$

| $(cp\text{-}no\text{-}confl)\ cdcl_W\text{-}merge\text{-}cp^{**}\ R\ V$ **and** $conflicting\ V = None$

| $(cp\text{-}confl)\ U$ **where** $cdcl_W\text{-}merge\text{-}cp^{**}\ R\ U$ **and** $conflict\ U\ V$

using $rtranclp\text{-}cdcl_W\text{-}s'\text{-}no\text{-}step\text{-}cdcl_W\text{-}s'\text{-}without\text{-}decide\text{-}decomp\text{-}into\text{-}cdcl_W\text{-}merge[OF$
 $\langle cdcl_W\text{-}s'^{**}\ R\ V \rangle\ assms]$ **by** $auto$

then show $?fw$

proof $cases$

case $fw\text{-}no\text{-}confl$

then show $?thesis$ **using** $n\text{-}s$ **unfolding** $full\text{-}def$ **by** $blast$

next

case $fw\text{-}confl$

then show $?thesis$ **using** $n\text{-}s$ **unfolding** $full\text{-}def$ **by** $blast$

next

case $fw\text{-}dec\text{-}confl$

have $cdcl_W\text{-}merge\text{-}cp\ U\ V$

using $n\text{-}s\text{-}bj$ **by** ($metis\ cdcl_W\text{-}merge\text{-}cp\text{-}simps\ full\text{-}unfold\ fw\text{-}dec\text{-}confl(5)$)

```

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
  using fw-s-cp unfolding full-unfold fw-s-cp
  by (metis (no-types) 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 cdclW** R V using rtranclp-mono[of cdclW-merge-stgy cdclW**]
  cdclW-merge-stgy-rtranclp-cdclW unfolding full-def by auto
then have inv': cdclW-all-struct-inv V using inv rtranclp-cdclW-all-struct-inv-inv by blast
have cdclW-s'** R V
  using ⟨?fw⟩ by (simp add: full-def inv rtranclp-cdclW-merge-stgy-rtranclp-cdclW-s')
moreover have no-step cdclW-s' V
proof cases
  assume conflicting V = None
  then show ?thesis
    by (metis inv' ⟨full cdclW-merge-stgy R V⟩ full-def
      no-step-cdclW-merge-stgy-no-step-cdclW-s')
next
  assume confl-V: conflicting V ≠ None
  then have no-step cdclW-bj V
    using rtranclp-cdclW-merge-stgy-no-step-cdclW-bj by (meson ⟨full cdclW-merge-stgy R V⟩
      assms(1) full-def)
  then show ?thesis using confl-V by (fastforce simp: cdclW-s'.simps full1-def cdclW-cp.simps
    dest!: tranclpD elim: rulesE)
qed
ultimately show ?s' unfolding full-def by blast
qed

lemma full-cdclW-stgy-full-cdclW-merge:
  assumes
    conflicting R = None and
    cdclW-all-struct-inv R

```


shows $\text{full_cdcl}_W\text{-stgy } R \ V \longleftrightarrow \text{full_cdcl}_W\text{-merge-stgy } R \ V$
by (*simp add: assms full-cdcl_W-s'-full-cdcl_W-merge-restart full-cdcl_W-stgy-iff-full-cdcl_W-s'*)

lemma *full-cdcl_W-merge-stgy-final-state-conclusive'*:

fixes $S' :: 'st$

assumes

full: $\text{full_cdcl}_W\text{-merge-stgy } (\text{init-state } N) \ S'$ **and**

no-d: $\text{distinct-mset-mset } N$

shows $(\text{conflicting } S' = \text{Some } \{\#\} \wedge \text{unsatisfiable } (\text{set-mset } N))$

$\vee (\text{conflicting } S' = \text{None} \wedge \text{trail } S' \models_{\text{asm}} N \wedge \text{satisfiable } (\text{set-mset } N))$

proof –

have $\text{cdcl}_W\text{-all-struct-inv } (\text{init-state } N)$

using *no-d* **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ **by** *auto*

moreover have $\text{conflicting } (\text{init-state } N) = \text{None}$

by *auto*

ultimately show *?thesis*

using *full full-cdcl_W-stgy-final-state-conclusive-from-init-state*

full-cdcl_W-stgy-full-cdcl_W-merge no-d **by** *presburger*

qed

end

end

theory *CDCL-W-Restart*

imports *CDCL-W-Merge*

begin

6.3.5 Adding Restarts

locale *cdcl_W-restart* =

conflict-driven-clause-learning_W

— functions for the state:

— access functions:

trail init-clss learned-clss backtrack-lvl conflicting

— changing state:

cons-trail tl-trail add-learned-cls remove-cls update-backtrack-lvl

update-conflicting

— get state:

init-state

for

trail :: $'st \Rightarrow ('v, 'v \text{ clause}) \text{ ann-lits}$ **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 :: $('v, 'v \text{ clause}) \text{ ann-lit} \Rightarrow 'st \Rightarrow 'st$ **and**

tl-trail :: $'st \Rightarrow 'st$ **and**

add-learned-cls :: $'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$ **and**

remove-cls :: $'v \text{ clause} \Rightarrow 'st \Rightarrow 'st$ **and**

update-backtrack-lvl :: $\text{nat} \Rightarrow 'st \Rightarrow 'st$ **and**

update-conflicting :: $'v \text{ clause option} \Rightarrow 'st \Rightarrow 'st$ **and**

init-state :: $'v \text{ clauses} \Rightarrow 'st +$

fixes $f :: \text{nat} \Rightarrow \text{nat}$

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:

(*cdcl_W-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 *cdcl_W-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!*: *relopwp-imp-rtrancpl cdcl_W-merge-stgy-trancpl-cdcl_W-merge trancpl-into-rtrancpl*
rtrancpl-cdcl_W-merge-stgy-rtrancpl-cdcl_W-merge rtrancpl-cdcl_W-merge-trancpl-cdcl_W-merge-restart
fw-r-rf cdcl_W-rf.restart
simp: *full1-def*)

lemma *cdcl_W-merge-with-restart-rtrancpl-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!*: *relopwp-imp-rtrancpl rtrancpl-cdcl_W-merge-stgy-rtrancpl-cdcl_W cdcl_W.rf*
cdcl_W-rf.restart trancpl-into-rtrancpl 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-mm (init-clss S))*

proof

fix *C*

assume *C*: *C \in set-mset (learned-clss S)*

have *distinct-mset C*

using *C inv unfolding cdcl_W-all-struct-inv-def distinct-cdcl_W-state-def distinct-mset-set-def*

by *auto*

moreover **have** \neg *tautology C*

using *C inv unfolding cdcl_W-all-struct-inv-def cdcl_W-learned-clause-def* **by** *auto*

moreover

have *atms-of C \subseteq atms-of-mm (learned-clss S)*

using *C* **by** *auto*

then **have** *atms-of C \subseteq atms-of-mm (init-clss S)*

using *inv unfolding cdcl_W-all-struct-inv-def no-strange-atm-def* **by** *force*

moreover **have** *finite (atms-of-mm (init-clss S))*

using *inv unfolding cdcl_W-all-struct-inv-def* **by** *auto*

ultimately **show** *C \in simple-clss (atms-of-mm (init-clss S))*

using *distinct-mset-not-tautology-implies-in-simple-clss simple-clss-mono*

by *blast*

qed

lemma *cdcl_W-merge-with-restart-init-clss*:

cdcl_W-merge-with-restart S T \implies *cdcl_W-M-level-inv (fst S)* \implies
init-clss (fst S) = init-clss (fst T)

using *cdcl_W-merge-with-restart-rtrancplp-cdcl_W rtrancplp-cdcl_W-init-clss* **by** *blast*

lemma

wf {(T, S). cdcl_W-all-struct-inv (fst S) \wedge cdcl_W-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 *wf-iff-no-infinite-down-chain* **by** *fast*

{ fix *i*

have *init-clss (fst (g i)) = init-clss (fst (g 0))*

apply (*induction i*)

apply *simp*

using *g inv unfolding cdcl_W-all-struct-inv-def* **by** (*metis cdcl_W-merge-with-restart-init-clss*)

} note *init-g = this*

let *?S = g 0*

have *finite (atms-of-mm (init-clss (fst ?S)))*

using *inv unfolding cdcl_W-all-struct-inv-def* **by** *auto*

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-Suc cdcl_W-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*: *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 le-iff-add*)

obtain *k* **where**

f-g-k: $f\ (\text{snd } (g\ k)) > \text{card } (\text{simple-clss } (\text{atms-of-mm } (\text{init-clss } (\text{fst } ?S))))$ **and**

$k > \text{card } (\text{simple-clss } (\text{atms-of-mm } (\text{init-clss } (\text{fst } ?S))))$

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 cdcl_W-merge-stgy (fst (g i))*

with *g[of i]*

have *False*

proof (*induction rule: cdcl_W-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** *cdcl_W-merge-stgy S S'*

using *H c* **by** (*metis gr-implies-not0 relpowp-E2*)

then show *False* **using** *n-s* **by** *auto*

next

case (*restart-full S T*)

then show *False* **unfolding** *full1-def* **by** (*auto dest: trancplD*)

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**

$cdcl_W\text{-merge-stgy} : (cdcl_W\text{-merge-stgy} \rightsquigarrow m) (fst (g\ k))\ T$
using $g[of\ k]\ H[of\ Suc\ k]$ **by** $(force\ simp : cdcl_W\text{-merge-with-restart.simps}\ full1\text{-def})$
have $cdcl_W\text{-merge-stgy}^{**} (fst (g\ k))\ T$
using $cdcl_W\text{-merge-stgy}\ relpowp\text{-imp-rtrancpl}$ **by** $metis$
then have $cdcl_W\text{-all-struct-inv}\ T$
using $inv[of\ k]\ rtrancpl\text{-}cdcl_W\text{-all-struct-inv-inv}\ rtrancpl\text{-}cdcl_W\text{-merge-stgy-rtrancpl}\text{-}cdcl_W$
by $blast$
moreover have $card (set\text{-}mset (learned\text{-}clss\ T)) - card (set\text{-}mset (learned\text{-}clss (fst (g\ k))))$
 $> card (simple\text{-}clss (atms\text{-}of\text{-}mm (init\text{-}clss (fst\ ?S))))$
unfolding $m[symmetric]$ **using** $\langle m > f\ (snd (g\ k)) \rangle\ f\text{-}g\text{-}k$ **by** $linarith$
then have $card (set\text{-}mset (learned\text{-}clss\ T))$
 $> card (simple\text{-}clss (atms\text{-}of\text{-}mm (init\text{-}clss (fst\ ?S))))$
by $linarith$
moreover
have $init\text{-}clss (fst (g\ k)) = init\text{-}clss\ T$
using $\langle cdcl_W\text{-merge-stgy}^{**} (fst (g\ k))\ T \rangle\ rtrancpl\text{-}cdcl_W\text{-merge-stgy-rtrancpl}\text{-}cdcl_W$
 $rtrancpl\text{-}cdcl_W\text{-init-clss}\ inv$ **unfolding** $cdcl_W\text{-all-struct-inv-def}$ **by** $blast$
then have $init\text{-}clss (fst\ ?S) = init\text{-}clss\ T$
using $init\text{-}g[of\ k]$ **by** $auto$
ultimately show $False$
using $cdcl_W\text{-all-struct-inv-learned-clss-bound}$
by $(simp\ add : \langle finite (atms\text{-}of\text{-}mm (init\text{-}clss (fst (g\ 0)))) \rangle\ simple\text{-}clss\text{-}finite$
 $card\text{-}mono\ leD)$

qed

lemma $cdcl_W\text{-merge-with-restart-distinct-mset-clauses}$:

assumes $invR : cdcl_W\text{-all-struct-inv}\ (fst\ R)$ **and**
 $st : cdcl_W\text{-merge-with-restart}\ R\ S$ **and**
 $dist : distinct\text{-}mset\ (clauses\ (fst\ R))$ **and**
 $R : trail\ (fst\ R) = []$
shows $distinct\text{-}mset\ (clauses\ (fst\ S))$
using $assms(2,1,3,4)$
proof $(induction)$
case $(restart\text{-}full\ S\ T)$
then show $?case$ **using** $rtrancpl\text{-}cdcl_W\text{-merge-stgy-distinct-mset-clauses}[of\ S\ T]$ **unfolding** $full1\text{-def}$
by $(auto\ dest : trancpl\text{-}into\text{-}rtrancpl)$
next
case $(restart\text{-}step\ T\ S\ n\ U)$
then have $distinct\text{-}mset\ (clauses\ T)$
using $rtrancpl\text{-}cdcl_W\text{-merge-stgy-distinct-mset-clauses}[of\ S\ T]$ **unfolding** $full1\text{-def}$
by $(auto\ dest : relpowp\text{-}imp\text{-}rtrancpl)$
then show $?case$ **using** $\langle restart\ T\ U \rangle$ **unfolding** $clauses\text{-}def$
by $(metis\ distinct\text{-}mset\text{-}union\ fstI\ restartE\ subset\text{-}mset.le\text{-}iff\text{-}add\ union\text{-}assoc)$
qed

inductive $cdcl_W\text{-with-restart}$ **where**

$restart\text{-}step$:

$(cdcl_W\text{-stgy} \rightsquigarrow (card (set\text{-}mset (learned\text{-}clss\ T)) - card (set\text{-}mset (learned\text{-}clss\ S))))\ S\ T \implies$
 $card (set\text{-}mset (learned\text{-}clss\ T)) - card (set\text{-}mset (learned\text{-}clss\ S)) > f\ n \implies$
 $restart\ T\ U \implies$
 $cdcl_W\text{-with-restart}\ (S, n)\ (U, Suc\ n) \mid$
 $restart\text{-}full : full1\ cdcl_W\text{-stgy}\ S\ T \implies cdcl_W\text{-with-restart}\ (S, n)\ (T, Suc\ n)$

lemma $cdcl_W\text{-with-restart-rtrancpl-cdcl_W}$:

$cdcl_W\text{-with-restart}\ S\ T \implies cdcl_W^{**} (fst\ S)\ (fst\ T)$
apply $(induction\ rule : cdcl_W\text{-with-restart.induct})$

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-with-restart $S\ T \implies \text{snd } T = 1 + \text{snd } S$
 by (induction rule: cdcl_W-with-restart.induct) auto

lemma full1 cdcl_W-stgy $S\ T \implies \text{cdcl}_W\text{-with-restart } (S, n)\ (T, \text{Suc } n)$
 using restart-full by blast

lemma cdcl_W-with-restart-init-clss:
 cdcl_W-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 cdcl_W-with-restart-rtrancp-cdcl_W rtrancp-cdcl_W-init-clss by blast

lemma
 wf {(T, S). cdcl_W-all-struct-inv (fst S) \wedge cdcl_W-with-restart $S\ T$ }
proof (rule ccontr)
 assume $\neg ?thesis$
 then obtain g where
 $g: \bigwedge i. \text{cdcl}_W\text{-with-restart } (g\ i)\ (g\ (\text{Suc } i))$ and
 $\text{inv}: \bigwedge i. \text{cdcl}_W\text{-all-struct-inv } (\text{fst } (g\ i))$
 unfolding 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 (induction i)
 apply simp
 using g inv unfolding cdcl_W-all-struct-inv-def by (metis cdcl_W-with-restart-init-clss)
 } note $\text{init-g} = \text{this}$
 let $?S = g\ 0$
 have $\text{finite } (\text{atms-of-mm } (\text{init-clss } (\text{fst } ?S)))$
 using inv unfolding cdcl_W-all-struct-inv-def by auto
 have $\text{snd-g}: \bigwedge i. \text{snd } (g\ i) = i + \text{snd } (g\ 0)$
 apply (induct-tac i)
 apply simp
 by (metis Suc-eq-plus1-left add-Suc cdcl_W-with-restart-increasing-number g)
 then have $\text{snd-g-0}: \bigwedge i. i > 0 \implies \text{snd } (g\ i) = i + \text{snd } (g\ 0)$
 by blast
 have $\text{unbounded-f-g}: \text{unbounded } (\lambda i. f\ (\text{snd } (g\ i)))$
 using f unfolding bounded-def by (metis add.commute f less-or-eq-imp-le snd-g
 not-bounded-nat-exists-larger not-le le-iff-add)

obtain k where
 $f\text{-g-}k: f\ (\text{snd } (g\ k)) > \text{card } (\text{simple-clss } (\text{atms-of-mm } (\text{init-clss } (\text{fst } ?S))))$ and
 $k > \text{card } (\text{simple-clss } (\text{atms-of-mm } (\text{init-clss } (\text{fst } ?S))))$
 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 cdcl_W-stgy (fst (g i))
 with $g[\text{of } i]$
 have False
proof (induction rule: cdcl_W-with-restart.induct)
 case (restart-step $T\ S\ n$) note $H = \text{this}(1)$ and $c = \text{this}(2)$ and $n\text{-s} = \text{this}(4)$
 obtain S' where cdcl_W-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: trancpD)
  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-stgy  $\sim$  m) (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-rtrancp by metis
then have cdclW-all-struct-inv T
  using inv[of k] rtrancp-cdclW-all-struct-inv-inv rtrancp-cdclW-stgy-rtrancp-cdclW by blast
moreover have card (set-mset (learned-clss T)) - card (set-mset (learned-clss (fst (g k))))
  > card (simple-clss (atms-of-mm (init-clss (fst ?S))))
  unfolding m[symmetric] using  $\langle m > f \text{ (snd (g k))} \rangle$  f-g-k by linarith
then have card (set-mset (learned-clss T))
  > card (simple-clss (atms-of-mm (init-clss (fst ?S))))
  by linarith
moreover
  have init-clss (fst (g k)) = init-clss T
    using  $\langle \text{cdcl}_W\text{-stgy}^{**} \text{ (fst (g k)) } T \rangle$  rtrancp-cdclW-stgy-rtrancp-cdclW rtrancp-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:  $\langle \text{finite (atms-of-mm (init-clss (fst (g 0))))} \rangle$  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 rtrancp-cdclW-stgy-distinct-mset-clauses[of S T] unfolding full1-def
    by (auto dest: trancp-into-rtrancp)
next
  case (restart-step T S n U)
  then have distinct-mset (clauses T) using rtrancp-cdclW-stgy-distinct-mset-clauses[of S T]
    unfolding full1-def by (auto dest: relpowp-imp-rtrancp)
  then show ?case using (restart T U) unfolding clauses-def
    by (metis distinct-mset-union fstI restartE subset-mset.le-iff-add union-assoc)
qed
end

```

locale *luby-sequence* =

```

fixes ur :: nat
assumes ur > 0
begin

lemma exists-luby-decomp:
  fixes i :: nat
  shows  $\exists k :: \text{nat}. (2^{\wedge} (k - 1) \leq i \wedge i < 2^{\wedge} k - 1) \vee i = 2^{\wedge} k - 1$ 
proof (induction i)
  case 0
  then show ?case
    by (rule exI[of - 0], simp)
next
  case (Suc n)
  then obtain k where  $2^{\wedge} (k - 1) \leq n \wedge n < 2^{\wedge} k - 1 \vee n = 2^{\wedge} k - 1$ 
    by blast
  then consider
    (st-interv)  $2^{\wedge} (k - 1) \leq n$  and  $n \leq 2^{\wedge} k - 2$ 
  | (end-interv)  $2^{\wedge} (k - 1) \leq n$  and  $n = 2^{\wedge} k - 2$ 
  | (pow2)  $n = 2^{\wedge} k - 1$ 
    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
           $(2^{\wedge} (k - 1) \leq n \wedge n < 2^{\wedge} k - 1 \vee n = 2^{\wedge} k - 1)$  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)
      next
      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  $\exists k. i = 2^{\wedge} k - 1$ 
    then  $2^{\wedge} ((\text{SOME } k. i = 2^{\wedge} k - 1) - 1)$ 
    else luby-sequence-core  $(i - 2^{\wedge} ((\text{SOME } k. 2^{\wedge} (k-1) \leq i \wedge i < 2^{\wedge} k - 1) - 1) + 1)$ )
by auto
termination
proof (relation less-than, goal-cases)
  case 1
  then show ?case by auto
next

```

```

case (2 i)
let ?k = SOME k.  $2^{\wedge} (k - 1) \leq i \wedge i < 2^{\wedge} k - 1$ 
have  $2^{\wedge} (?k - 1) \leq i \wedge i < 2^{\wedge} ?k - 1$ 
  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:  $(1::\text{nat}) \leq 2^{\wedge} (?k - 1)$ 
    using one-le-numeral by blast
  have f2:  $i - 2^{\wedge} (?k - 1) + 2^{\wedge} (?k - 1) = i$ 
    using  $2^{\wedge} (?k - 1) \leq i \wedge i < 2^{\wedge} ?k - 1$  le-add-diff-inverse2 by blast
  have f3:  $2^{\wedge} ?k - 1 \neq \text{Suc } 0$ 
    using f1  $2^{\wedge} (?k - 1) \leq i \wedge i < 2^{\wedge} ?k - 1$  by linarith
  have  $2^{\wedge} ?k - (1::\text{nat}) \neq 0$ 
    using  $2^{\wedge} (?k - 1) \leq i \wedge i < 2^{\wedge} ?k - 1$  gr-implies-not0 by blast
  then have f4:  $2^{\wedge} ?k \neq (1::\text{nat})$ 
    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  $2^{\wedge} (?k - 1) \neq \text{Suc } 0$ 
    using f5 f3 by presburger
  then have  $\text{Suc } 0 < 2^{\wedge} (?k - 1)$ 
    using f1 by linarith
  then show ?thesis
    using f2 less-than-iff by presburger
qed
qed

function natlog2 :: nat  $\Rightarrow$  nat where
natlog2 n = (if n = 0 then 0 else 1 + natlog2 (n div 2))
  using not0-implies-Suc by auto
termination by (relation measure ( $\lambda n. n$ )) auto

declare natlog2.simps[simp del]

declare luby-sequence-core.simps[simp del]

lemma two-pover-n-eq-two-power-n'-eq:
  assumes H:  $(2::\text{nat})^{\wedge} (k::\text{nat}) - 1 = 2^{\wedge} k' - 1$ 
  shows  $k' = k$ 
proof -
  have  $(2::\text{nat})^{\wedge} (k::\text{nat}) = 2^{\wedge} k'$ 
    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  $(2^{\wedge} k - 1) = 2^{\wedge} (k-1)$  (is ?L = ?K)
proof -
  have decomp:  $\exists ka. 2^{\wedge} k - 1 = 2^{\wedge} ka - 1$ 
    by auto

```



```

have ?L = 2^((SOME k'. (2::nat)^k - 1 = 2^k' - 1) - 1)
  apply (subst luby-sequence-core.simps, subst decomp)
  by simp
moreover have (SOME k'. (2::nat)^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 ^ (k - Suc 0) ≤ i and
  k': i < 2 ^ k' - Suc 0 and
  k-k': k > k'
shows False
proof -
  have 2 ^ k' - Suc 0 < 2 ^ (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 ^ (k - 1) ≤ i and
  i-k: i < 2 ^ k - 1
shows luby-sequence-core i = luby-sequence-core (i - 2 ^ (k - 1) + 1)
proof -
  have H: ¬ (∃ ka. i = 2 ^ ka - 1)
  proof (rule ccontr)
    assume ¬ ?thesis
    then obtain k':nat where k': i = 2 ^ k' - 1 by blast
    have (2::nat) ^ k' - 1 < 2 ^ k - 1
      using i-k unfolding k'.
    then have (2::nat) ^ k' < 2 ^ k
      by linarith
    then have k' < k
      by simp
    have 2 ^ (k - 1) ≤ 2 ^ k' - (1::nat)
      using k-i unfolding k'.
    then have (2::nat) ^ (k-1) < 2 ^ 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 ⟨k' < k⟩ ⟨k-1 < k'⟩ by linarith
  qed
  have ∧k k'. 2 ^ (k - Suc 0) ≤ i ⟹ i < 2 ^ k - Suc 0 ⟹ 2 ^ (k' - Suc 0) ≤ i ⟹
    i < 2 ^ k' - Suc 0 ⟹ k = k'
    by (meson different-luby-decomposition-false linorder-neqE-nat)
  then have k: (SOME k. 2 ^ (k - Suc 0) ≤ i ∧ i < 2 ^ k - Suc 0) = k
    using k-i i-k by auto
  show ?thesis
    apply (subst luby-sequence-core.simps[of i], subst H)
    by (simp add: k)

```

qed

lemma *unbounded-luby-sequence-core: unbounded luby-sequence-core*
unfolding *bounded-def*

proof

assume $\exists b. \forall n. \text{luby-sequence-core } n \leq b$
then obtain b **where** $b: \bigwedge n. \text{luby-sequence-core } n \leq b$
by *metis*
have $\text{luby-sequence-core } (2^{b+1} - 1) = 2^b$
using *luby-sequence-core-two-power-minus-one[of b+1]* **by** *simp*
moreover have $(2::\text{nat})^b > b$
by (*induction b*) *auto*
ultimately show *False* **using** $b[\text{of } 2^{b+1} - 1]$ **by** *linarith*

qed

abbreviation *luby-sequence* :: $\text{nat} \Rightarrow \text{nat}$ **where**

luby-sequence $n \equiv ur * \text{luby-sequence-core } n$

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 $0: (0::\text{nat}) = 2^0 - 1$
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** $2^k - 1 \leq \text{Suc } n$ **and** $\text{Suc } n < 2^{k+1} - 1$
| (*pow2*) k **where** $\text{Suc } n = 2^{k+1} - 1$
using *exists-luby-decomp[of Suc n]* **by** *auto*

then show *?case*

proof *cases*

case *pow2*

show *?thesis*

using *luby-sequence-core-two-power-minus-one pow2* **by** *auto*

next

case *interv*

have $n: \text{Suc } n - 2^k + 1 < \text{Suc } n$

by (*metis Suc-1 Suc-eq-plus1 add.commute add-diff-cancel-left' add-less-mono1 gr0I*
interv(1) interv(2) le-add-diff-inverse2 less-Suc-eq not-le power-0 power-one-right
power-strict-increasing-iff)

show *?thesis*

apply (*subst luby-sequence-core-not-two-power-minus-one[OF interv]*)

using *IH n* **by** *auto*

```

    qed
qed
end

locale luby-sequence-restart =
  luby-sequence ur +
  conflict-driven-clause-learningW
  — functions for the state:
  — access functions:
  trail init-clss learned-clss backtrack-lvl conflicting
  — changing state:
  cons-trail tl-trail add-learned-cls remove-cls update-backtrack-lvl
  update-conflicting

  — get state:
  init-state
for
  ur :: nat and
  trail :: 'st ⇒ ('v, 'v clause) ann-lits and
  hd-trail :: 'st ⇒ ('v, 'v clause) ann-lit 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, 'v clause) ann-lit ⇒ 'st ⇒ 'st and
  tl-trail :: 'st ⇒ 'st and
  add-learned-cls :: 'v clause ⇒ 'st ⇒ 'st and
  remove-cls :: 'v clause ⇒ 'st ⇒ 'st and
  update-backtrack-lvl :: nat ⇒ 'st ⇒ 'st and
  update-conflicting :: 'v clause option ⇒ 'st ⇒ 'st and

  init-state :: 'v clauses ⇒ '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

```

6.4 Incremental SAT solving

```

locale stateW-adding-init-clause =
  stateW
  — functions about the state:
  — getter:
  trail init-clss learned-clss backtrack-lvl conflicting
  — setter:
  cons-trail tl-trail add-learned-cls remove-cls update-backtrack-lvl
  update-conflicting

```

— Some specific states:

```

init-state
for
  trail :: 'st  $\Rightarrow$  ('v, 'v clause) ann-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, 'v clause) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
  tl-trail :: '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 +
fixes
  add-init-clss :: 'v clause  $\Rightarrow$  'st  $\Rightarrow$  'st
assumes
  add-init-clss:
    state st = (M, N, U, S')  $\implies$ 
    state (add-init-clss C st) = (M, {#C#} + N, U, S')
begin

lemma
  trail-add-init-clss[simp]:
    trail (add-init-clss C st) = trail st and
  init-clss-add-init-clss[simp]:
    init-clss (add-init-clss C st) = {#C#} + init-clss st
    and
  learned-clss-add-init-clss[simp]:
    learned-clss (add-init-clss C st) = learned-clss st and
  backtrack-lvl-add-init-clss[simp]:
    backtrack-lvl (add-init-clss C st) = backtrack-lvl st and
  conflicting-add-init-clss[simp]:
    conflicting (add-init-clss C st) = conflicting st
using add-init-clss[of st - - - C] by (cases state st; auto)+

lemma clauses-add-init-clss[simp]:
  clauses (add-init-clss N S) = {#N#} + init-clss S + learned-clss S
  unfolding clauses-def by auto

lemma reduce-trail-to-add-init-clss[simp]:
  trail (reduce-trail-to F (add-init-clss C S)) = trail (reduce-trail-to F S)
  by (rule trail-eq-reduce-trail-to-eq) auto

lemma conflicting-add-init-clss-iff-conflicting[simp]:
  conflicting (add-init-clss C S) = None  $\longleftrightarrow$  conflicting S = None
  by fastforce+
end

locale conflict-driven-clause-learning-with-adding-init-clauseW =
  stateW-adding-init-clause

```

— functions for the state:
 — access functions:
trail init-clss learned-clss backtrack-lvl conflicting
 — changing state:
cons-trail tl-trail add-learned-cls remove-cls update-backtrack-lvl
update-conflicting

 — get state:
init-state
 — Adding a clause:
add-init-cls
for
trail :: 'st \Rightarrow ('v, 'v clause) ann-lits and
hd-trail :: 'st \Rightarrow ('v, 'v clause) ann-lit 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, 'v clause) ann-lit \Rightarrow 'st \Rightarrow 'st and
tl-trail :: 'st \Rightarrow 'st and
add-learned-cls :: 'v clause \Rightarrow 'st \Rightarrow 'st and
remove-cls :: 'v clause \Rightarrow 'st \Rightarrow 'st and
update-backtrack-lvl :: nat \Rightarrow 'st \Rightarrow 'st and
update-conflicting :: 'v clause option \Rightarrow 'st \Rightarrow 'st and

init-state :: 'v clauses \Rightarrow 'st and
add-init-cls :: 'v clause \Rightarrow 'st \Rightarrow 'st
begin

sublocale *conflict-driven-clause-learning_W*
by *unfold-locales*

 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 $S \longleftrightarrow$
conflict-is-false-with-level S
 \wedge *no-clause-is-false* S
 \wedge *no-smaller-confl* S
 \wedge *no-clause-is-false* S

lemma *cdcl_W-stgy-cdcl_W-stgy-invariant*:
assumes
cdcl_W: cdcl_W-stgy S T **and**
inv-s: cdcl_W-stgy-invariant S **and**
inv: cdcl_W-all-struct-inv S
shows
cdcl_W-stgy-invariant T
unfolding *cdcl_W-stgy-invariant-def cdcl_W-all-struct-inv-def* **apply** (*intro conjI*)
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]
using *cdcl_W cdcl_W-stgy-not-non-negated-init-clss* **apply** *simp*
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
*cdcl_W: cdcl_W-stgy** S T and*
inv-s: cdcl_W-stgy-invariant S and
inv: cdcl_W-all-struct-inv S
shows
cdcl_W-stgy-invariant T
using *assms* **apply** (*induction*)
apply *simp*
using *cdcl_W-stgy-cdcl_W-stgy-invariant 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 *update-backtrack-lvl (backtrack-lvl S - 1) S*

When we add a new clause, we reduce the trail until we get to the first literal included in C. Then we can mark the conflict.

fun *cut-trail-wrt-clause* **where**
cut-trail-wrt-clause C [] S = S |
cut-trail-wrt-clause C (Decided L # M) S =
(if -L \in # C then S
else cut-trail-wrt-clause C M (decr-bt-lvl (tl-trail S))) |
cut-trail-wrt-clause C (Propagated L - # M) S =
(if -L \in # C then S
else cut-trail-wrt-clause C M (tl-trail S))

definition *add-new-clause-and-update* :: *'v clause \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: ann-lit-list-induct*)

case *Nil*

then show *?case* **by** *simp*

next

case (*Decided 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 (Propagated 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-decided:
  assumes
    backtrack-lvl T = count-decided (trail T)
  shows
    backtrack-lvl (cut-trail-wrt-clause C (trail T) T) =
      count-decided (trail (cut-trail-wrt-clause C (trail T) T))
  using assms
proof (induction trail T arbitrary: T rule: ann-lit-list-induct)
  case Nil
  then show ?case by simp
next
  case (Decided 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 (Propagated 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-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: ann-lit-list-induct)
  case Nil
  then show ?case by simp
next
  case (Decided 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 clause 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 blast
  end
end

```

```

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 simp: count-eq-zero-iff)
then show ?thesis
  using IH true-annots-true-cls M by (auto simp: CNot-def)
qed
next
case (Propagated L l M) note  $IH = \text{this}(1)[\text{of } tl\text{-trail } T]$  and  $M = \text{this}(2)[\text{symmetric}]$  and  $bt = \text{this}(3)$ 
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 clause 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 blast
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 simp: count-eq-zero-iff)
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*:

$$((\forall L \in \# C. -L \notin \text{lits-of-} l (\text{trail } T)) \wedge \text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T) = []) \\ \vee (-\text{lit-of } (\text{hd } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T))) \in \# C \\ \wedge \text{length } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T)) \geq 1)$$

proof (*induction trail T arbitrary:T rule: ann-lit-list-induct*)

```

case Nil
then show ?case by simp
next
case (Decided L M) note  $IH = \text{this}(1)[\text{of } \text{decr-bt-lvl } (tl\text{-trail } T)]$  and  $M = \text{this}(2)[\text{symmetric}]$ 
then show ?case by simp force
next
case (Propagated L l M) note  $IH = \text{this}(1)[\text{of } tl\text{-trail } T]$  and  $M = \text{this}(2)[\text{symmetric}]$ 
then show ?case by simp force
qed

```

We can fully run *cdcl_W*-s or add a clause. Remark that we use *cdcl_W*-s to avoid an explicit *skip*, *resolve*, and *backtrack* normalisation to get rid of the conflict *C* if possible.

inductive *incremental-cdcl_W* :: '*st* \Rightarrow '*st* \Rightarrow *bool* **for** *S* **where**

add-conf:

$$\text{trail } S \models_{asm} \text{init-clss } S \Longrightarrow \text{distinct-mset } C \Longrightarrow \text{conflicting } S = \text{None} \Longrightarrow \\ \text{trail } S \models_{as} \text{CNot } C \Longrightarrow \\ \text{full } cdcl_W\text{-stgy} \\ (\text{update-conflicting } (\text{Some } C) \\ (\text{add-init-cls } C (\text{cut-trail-wrt-clause } C (\text{trail } S) S))) T \Longrightarrow \\ \text{incremental-cdcl}_W S T \mid$$

add-no-conf:

$$\text{trail } S \models_{asm} \text{init-clss } S \Longrightarrow \text{distinct-mset } C \Longrightarrow \text{conflicting } S = \text{None} \Longrightarrow$$

$\neg \text{trail } S \models_{as} C \text{Not } C \implies$
 $\text{full } \text{cdcl}_W\text{-stgy } (\text{add-init-cls } C \ S) \ T \implies$
 $\text{incremental-cdcl}_W \ S \ T$

lemma *cdcl_W-all-struct-inv-add-new-clause-and-update-cdcl_W-all-struct-inv:*

assumes

$\text{inv-}T$: *cdcl_W-all-struct-inv* T **and**
 $\text{tr-}T\text{-}N[\text{simp}]$: $\text{trail } T \models_{asm} N$ **and**
 $\text{tr-}C[\text{simp}]$: $\text{trail } T \models_{as} C \text{Not } C$ **and**
 $[\text{simp}]$: *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 *trail-cut-trail-wrt-clause*[*of* $T \ C$] **by** *blast*

have $H[\text{dest}]$: $\bigwedge x. x \in \text{lits-of-l } (\text{trail } (\text{cut-trail-wrt-clause } C \ (\text{trail } T) \ T)) \implies$
 $x \in \text{lits-of-l } (\text{trail } T)$

using $\text{inv-}T$ *arg-cong*[*OF* M , *of* *lits-of-l*] **by** *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 $\text{inv-}T$ *arg-cong*[*OF* M , *of* *set*] **by** *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 $\text{inv-}T$ *arg-cong*[*OF* M , *of* *get-all-mark-of-propagated*] **by** *auto*

have $[\text{simp}]$: *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*
 $\text{cdcl}_W\text{-}M\text{-level-inv-def}$ **by** (*auto* 20 1)

have $M\text{-lev}$: *cdcl_W-M-level-inv* T

using $\text{inv-}T$ **unfolding** *cdcl_W-all-struct-inv-def* **by** *blast*

then have *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** *auto*

then have $[\text{simp}]$: *no-dup* $(\text{trail } (\text{cut-trail-wrt-clause } C \ (\text{trail } T) \ T))$
by *auto*

have *consistent-interp* $(\text{lits-of-l } (M @ \text{trail } (\text{cut-trail-wrt-clause } C \ (\text{trail } T) \ T)))$

using $M\text{-lev}$ **unfolding** *cdcl_W-M-level-inv-def* **unfolding** $M[\text{symmetric}]$ **by** *auto*

then have $[\text{simp}]$: *consistent-interp* $(\text{lits-of-l } (\text{trail } (\text{cut-trail-wrt-clause } C \ (\text{trail } T) \ T)))$

unfolding *consistent-interp-def* **by** *auto*

have $[\text{simp}]$: *cdcl_W-M-level-inv* $?T$

using $M\text{-lev}$ **unfolding** *cdcl_W-M-level-inv-def* **by** (*auto* *dest*: $H \ H'$
 simp : $M\text{-lev } \text{cdcl}_W\text{-}M\text{-level-inv-def } \text{cut-trail-wrt-clause-backtrack-lvl-length-decided}$)

have $[\text{simp}]$: $\bigwedge s. s \in \# \text{ learned-clss } T \implies \neg \text{tautology } s$

using $\text{inv-}T$ **unfolding** *cdcl_W-all-struct-inv-def* **by** *auto*

have *distinct-cdcl_W-state* T

using $\text{inv-}T$ **unfolding** *cdcl_W-all-struct-inv-def* **by** *auto*

then have $[\text{simp}]$: *distinct-cdcl_W-state* $?T$

unfolding *distinct-cdcl_W-state-def* **by** *auto*

```

have cdclW-conflicting T
  using inv-T unfolding cdclW-all-struct-inv-def by auto
have trail ?T  $\models_{as}$  CNot C
  by (simp add: cut-trail-wrt-clause-CNot-trail)
then have [simp]: cdclW-conflicting ?T
  unfolding cdclW-conflicting-def apply simp
  by (metis M  $\langle$ cdclW-conflicting T $\rangle$  append-assoc cdclW-conflicting-decomp(2))

have
  decomp-T: all-decomposition-implies-m (init-clss T) (get-all-ann-decomposition (trail T))
  using inv-T unfolding cdclW-all-struct-inv-def by auto
have all-decomposition-implies-m (init-clss ?T)
  (get-all-ann-decomposition (trail ?T))
  unfolding all-decomposition-implies-def
  proof clarify
    fix a b
    assume (a, b)  $\in$  set (get-all-ann-decomposition (trail ?T))
    from in-get-all-ann-decomposition-in-get-all-ann-decomposition-prepend[OF this, of M]
    obtain b' where
      (a, b' @ b)  $\in$  set (get-all-ann-decomposition (trail T))
      using M by auto
    then have unmark-l a  $\cup$  set-mset (init-clss T)  $\models_{ps}$  unmark-l (b' @ b)
      using decomp-T unfolding all-decomposition-implies-def by fastforce
    then have unmark-l a  $\cup$  set-mset (init-clss ?T)  $\models_{ps}$  unmark-l (b @ b')
      by (simp add: Un-commute)
    then show unmark-l a  $\cup$  set-mset (init-clss ?T)  $\models_{ps}$  unmark-l b
      by (auto simp: image-Un)
  qed
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  $\langle$ all-decomposition-implies-m (init-clss ?T)
  (get-all-ann-decomposition (trail ?T)) $\rangle$ 
  unfolding cdclW-all-struct-inv-def by (auto simp: add-new-clause-and-update-def)
qed

lemma cdclW-all-struct-inv-add-new-clause-and-update-cdclW-stgy-inv:
  assumes
    inv-s: cdclW-stgy-invariant T and
    inv: cdclW-all-struct-inv T and
    tr-T-N[simp]: trail T  $\models_{asm}$  N and
    tr-C[simp]: trail T  $\models_{as}$  CNot C and
    [simp]: distinct-mset C
  shows cdclW-stgy-invariant (add-new-clause-and-update C T)
    (is cdclW-stgy-invariant ?T')
  proof -
    have cdclW-all-struct-inv ?T'
      using cdclW-all-struct-inv-add-new-clause-and-update-cdclW-all-struct-inv assms by blast
    then have
      no-dup-cut-T[simp]: no-dup (trail (cut-trail-wrt-clause C (trail T) T)) and
      n-d[simp]: no-dup (trail T)
      using cdclW-M-level-inv-decomp(2) cdclW-all-struct-inv-def inv
      n-dup-no-dup-trail-cut-trail-wrt-clause by blast+
    then have trail (add-new-clause-and-update C T)  $\models_{as}$  CNot C

```

```

by (simp add: add-new-clause-and-update-def cut-trail-wrt-clause-CNot-trail
  cdclW-M-level-inv-def cdclW-all-struct-inv-def)
obtain MT where
  MT: trail T = MT @ trail (cut-trail-wrt-clause C (trail T) T)
  using trail-cut-trail-wrt-clause by blast
consider
  (false)  $\forall L \in \#C. - L \notin \text{ lits-of-l } (\text{trail } T) \text{ and }$ 
    trail (cut-trail-wrt-clause C (trail T) T) = []
| (not-false)
  - lit-of (hd (trail (cut-trail-wrt-clause C (trail T) T)))  $\in \# C$  and
    1  $\leq$  length (trail (cut-trail-wrt-clause C (trail T) T))
  using cut-trail-wrt-clause-hd-trail-in-or-empty-trail[of C T] by auto
then show ?thesis
proof cases
  case false note C = this(1) and empty-tr = this(2)
  then have [simp]: C = {#}
    by (simp add: in-CNot-implies-uminus(2) multiset-eqI)
  show ?thesis
    using empty-tr unfolding cdclW-stgy-invariant-def no-smaller-confl-def
      cdclW-all-struct-inv-def by (auto simp: add-new-clause-and-update-def)
next
  case not-false note C = this(1) and l = this(2)
  let ?L = - lit-of (hd (trail (cut-trail-wrt-clause C (trail T) T)))
  have L: get-level (trail (cut-trail-wrt-clause C (trail T) T)) (-?L)
    = count-decided (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: if-split-asm
    simp: rev-swap[symmetric] add-new-clause-and-update-def)

  have L': count-decided(trail (cut-trail-wrt-clause C
    (trail T) T))
    = backtrack-lvl (cut-trail-wrt-clause C (trail T) T)
  using  $\langle \text{cdcl}_W\text{-all-struct-inv } ?T' \rangle$  unfolding 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 M' D)
  then consider
    (DC) D = C
  | (D-T) D  $\in \#$  clauses T
  by (auto simp: clauses-def split: if-split-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') @ Decided K  $\#$  M = trail T
      using MT 1(1) by auto
    then show False
      using D-T  $\langle \text{no-smaller-confl } T \rangle$  1(3) unfolding no-smaller-confl-def by blast
  next

```

```

case DC note  $-\text{[simp]} = \text{this}$ 
then have  $\text{atm-of } (-?L) \in \text{atm-of } '(\text{lits-of-l } M)$ 
  using  $1(3) \text{ } C \text{ in-CNot-implies-uminus}(2)$  by blast
moreover
  have  $\text{lit-of } (\text{hd } (M' @ \text{Decided } K \# [])) = -?L$ 
    using  $1(1)[\text{symmetric}] \text{ inv}$ 
    by  $(\text{cases } M', \text{cases trail } (\text{add-init-cls } C$ 
       $(\text{cut-trail-wrt-clause } C (\text{trail } T) T)))$ 
     $(\text{auto dest! : arg-cong[of - \# - - hd] simp: hd-append cdcl_W-all-struct-inv-def}$ 
       $\text{cdcl}_W\text{-M-level-inv-def})$ 
  from  $\text{arg-cong}[OF \text{ this, of atm-of}]$ 
  have  $\text{atm-of } (-?L) \in \text{atm-of } '(\text{lits-of-l } (M' @ \text{Decided } K \# []))$ 
    by  $(\text{cases } (M' @ \text{Decided } K \# [])) \text{ auto}$ 
  moreover have  $\text{no-dup } (\text{trail } (\text{cut-trail-wrt-clause } C (\text{trail } T) T))$ 
    using  $\langle \text{cdcl}_W\text{-all-struct-inv } ?T' \rangle$  unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$ 
     $\text{cdcl}_W\text{-M-level-inv-def}$  by  $(\text{auto simp: add-new-clause-and-update-def})$ 
  ultimately show False
    unfolding  $1(1)[\text{symmetric, simplified}]$  by  $(\text{auto simp: lits-of-def})$ 
qed
qed
show ?thesis using  $L \text{ } L' \text{ } C$ 
  unfolding  $\text{cdcl}_W\text{-stgy-invariant-def } \text{cdcl}_W\text{-all-struct-inv-def}$ 
  by  $(\text{auto simp: add-new-clause-and-update-def intro: rev-bexI})$ 
qed
qed

```

lemma *full-cdcl_W-stgy-inv-normal-form:*

```

assumes
  full:  $\text{full } \text{cdcl}_W\text{-stgy } S \text{ } T$  and
  inv-s:  $\text{cdcl}_W\text{-stgy-invariant } S$  and
  inv:  $\text{cdcl}_W\text{-all-struct-inv } S$ 
shows  $\text{conflicting } T = \text{Some } \{\#\} \wedge \text{unsatisfiable } (\text{set-mset } (\text{init-clss } S))$ 
   $\vee \text{conflicting } T = \text{None} \wedge \text{trail } T \models_{\text{asm}} \text{init-clss } S \wedge \text{satisfiable } (\text{set-mset } (\text{init-clss } S))$ 
proof –
  have  $\text{no-step } \text{cdcl}_W\text{-stgy } T$ 
    using full unfolding full-def by blast
  moreover have  $\text{cdcl}_W\text{-all-struct-inv } T$  and inv-s:  $\text{cdcl}_W\text{-stgy-invariant } T$ 
    apply  $(\text{metis } \text{rtranclp-cdcl}_W\text{-stgy-rtranclp-cdcl}_W \text{ full full-def inv}$ 
       $\text{rtranclp-cdcl}_W\text{-all-struct-inv-inv})$ 
    by  $(\text{metis } \text{full full-def inv inv-s } \text{rtranclp-cdcl}_W\text{-stgy-cdcl}_W\text{-stgy-invariant})$ 
  ultimately have  $\text{conflicting } T = \text{Some } \{\#\} \wedge \text{unsatisfiable } (\text{set-mset } (\text{init-clss } T))$ 
     $\vee \text{conflicting } T = \text{None} \wedge \text{trail } T \models_{\text{asm}} \text{init-clss } T$ 
    using  $\text{cdcl}_W\text{-stgy-final-state-conclusive[of } T] \text{ full}$ 
    unfolding  $\text{cdcl}_W\text{-all-struct-inv-def } \text{cdcl}_W\text{-stgy-invariant-def full-def}$  by fast
  moreover have  $\text{consistent-interp } (\text{lits-of-l } (\text{trail } T))$ 
    using  $\langle \text{cdcl}_W\text{-all-struct-inv } T \rangle$  unfolding  $\text{cdcl}_W\text{-all-struct-inv-def } \text{cdcl}_W\text{-M-level-inv-def}$ 
    by auto
  moreover have  $\text{init-clss } S = \text{init-clss } T$ 
    using inv unfolding  $\text{cdcl}_W\text{-all-struct-inv-def}$ 
    by  $(\text{metis } \text{rtranclp-cdcl}_W\text{-stgy-no-more-init-clss full full-def})$ 
  ultimately show ?thesis
    by  $(\text{metis } \text{satisfiable-carac'} \text{ true-annot-def true-annots-def true-clss-def})$ 
qed

```

lemma *incremental-cdcl_W-inv:*

assumes

```

  inc: incremental-cdclW S T and
  inv: cdclW-all-struct-inv S and
  s-inv: cdclW-stgy-invariant S
shows
  cdclW-all-struct-inv T and
  cdclW-stgy-invariant T
using inc
proof (induction)
  case (add-confl C T)
  let ?T = (update-conflicting (Some C) (add-init-cls C
    (cut-trail-wrt-clause C (trail S) S)))
  have cdclW-all-struct-inv ?T and inv-s-T: cdclW-stgy-invariant ?T
  using add-confl.hyps(1,2,4) add-new-clause-and-update-def
  cdclW-all-struct-inv-add-new-clause-and-update-cdclW-all-struct-inv inv apply auto[1]
  using add-confl.hyps(1,2,4) add-new-clause-and-update-def
  cdclW-all-struct-inv-add-new-clause-and-update-cdclW-stgy-inv inv s-inv by auto
  case 1 show ?case
  by (metis add-confl.hyps(1,2,4,5) add-new-clause-and-update-def
    cdclW-all-struct-inv-add-new-clause-and-update-cdclW-all-struct-inv
    rtranclp-cdclW-all-struct-inv-inv rtranclp-cdclW-stgy-rtranclp-cdclW full-def inv)

  case 2 show ?case
  by (metis inv-s-T add-confl.hyps(1,2,4,5) add-new-clause-and-update-def
    cdclW-all-struct-inv-add-new-clause-and-update-cdclW-all-struct-inv full-def inv
    rtranclp-cdclW-stgy-cdclW-stgy-invariant)
next
  case (add-no-confl C T)
  case 1
  have cdclW-all-struct-inv (add-init-cls C S)
  using inv <distinct-mset C> unfolding cdclW-all-struct-inv-def no-strange-atm-def
  cdclW-M-level-inv-def distinct-cdclW-state-def cdclW-conflicting-def cdclW-learned-clause-def
  by (auto 9 1 simp: all-decomposition-implies-insert-single clauses-def)

  then show ?case
  using add-no-confl(5) unfolding full-def by (auto intro: rtranclp-cdclW-stgy-cdclW-all-struct-inv)
  case 2
  have nc:  $\forall M. (\exists K i M'. \text{trail } S = M' @ \text{Decided } K \# M) \longrightarrow \neg M \models_{as} CNot\ C$ 
  using < $\neg \text{trail } S \models_{as} CNot\ C$ >
  by (auto simp: true-annots-true-cls-def-iff-negation-in-model)

  have cdclW-stgy-invariant (add-init-cls C S)
  using s-inv < $\neg \text{trail } S \models_{as} CNot\ C$ > inv unfolding cdclW-stgy-invariant-def
  no-smaller-confl-def eq-commute[of - trail -] cdclW-M-level-inv-def cdclW-all-struct-inv-def
  by (auto simp: clauses-def nc)
  then show ?case
  by (metis <cdclW-all-struct-inv (add-init-cls C S)> add-no-confl.hyps(5) full-def
    rtranclp-cdclW-stgy-cdclW-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

```

    cdclW-stgy-invariant T
    using inc apply induction
    using inv apply simp
    using s-inv apply simp
    using incremental-cdclW-inv by blast+

lemma incremental-conclusive-state:
  assumes
    inc: incremental-cdclW S T and
    inv: cdclW-all-struct-inv S and
    s-inv: cdclW-stgy-invariant S
  shows conflicting T = Some {#}  $\wedge$  unsatisfiable (set-mset (init-clss T))
     $\vee$  conflicting T = None  $\wedge$  trail T  $\models_{asm}$  init-clss T  $\wedge$  satisfiable (set-mset (init-clss T))
  using inc
proof induction
  print-cases
  case (add-conf1 C T) note tr = this(1) and dist = this(2) and conf = this(3) and C = this(4) and
    full = this(5)

    have full cdclW-stgy T T
      using full unfolding full-def by auto
    then show ?case
      using full C conf dist tr
      by (metis full-cdclW-stgy-inv-normal-form incremental-cdclW.simps incremental-cdclW-inv(1)
        incremental-cdclW-inv(2) inv s-inv)
  next
  case (add-no-conf1 C T) note tr = this(1) and dist = this(2) and conf = this(3) and C = this(4)
    and full = this(5)

    have full cdclW-stgy T T
      using full unfolding full-def by auto
    then show ?case
      by (meson C conf dist full full-cdclW-stgy-inv-normal-form incremental-cdclW.add-no-conf1
        incremental-cdclW-inv(1) incremental-cdclW-inv(2) inv s-inv tr)
qed

lemma tranclp-incremental-correct:
  assumes
    inc: incremental-cdclW++ S T and
    inv: cdclW-all-struct-inv S and
    s-inv: cdclW-stgy-invariant S
  shows conflicting T = Some {#}  $\wedge$  unsatisfiable (set-mset (init-clss T))
     $\vee$  conflicting T = None  $\wedge$  trail T  $\models_{asm}$  init-clss T  $\wedge$  satisfiable (set-mset (init-clss T))
  using inc apply induction
  using assms incremental-conclusive-state apply blast
  by (meson incremental-conclusive-state inv rtranclp-incremental-cdclW-inv s-inv
    tranclp-into-rtranclp)

end

end

theory DPLL-CDCL-W-Implementation
imports Partial-Annotated-Clausal-Logic CDCL-W-Level
begin

```

Chapter 7

Implementation of DPLL and CDCL

We then reuse all the theorems to go towards an implementation using 2-watched literals:

- `CDCL_W_Abstract_State.thy` defines a better-suited state: the operation operating on it are more constrained, allowing simpler proofs and less edge cases later.

7.1 Simple List-Based Implementation of the DPLL and CDCL

The idea of the list-based implementation is to test the stack: the theories about the calculi, adapting the theorems to a simple implementation and the code exportation. The implementation are very simple and simply iterate over-and-over on lists.

7.1.1 Common Rules

Propagation

The following theorem holds:

lemma *lits-of-l-unfold*[*iff*]:

$(\forall c \in \text{set } C. -c \in \text{lits-of-l } Ms) \longleftrightarrow Ms \models_{as} CNot \ (mset \ C)$

unfolding *true-annots-def Ball-def true-annot-def CNot-def* **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* \Rightarrow (*'a, 'b*) *ann-lits* \Rightarrow *'a literal option*

where

is-unit-clause *l M* =

(*case List.filter* ($\lambda a. \text{atm-of } a \notin \text{atm-of ' lits-of-l } M$) *l of*
 a # [] \Rightarrow *if* *M* $\models_{as} CNot \ (mset \ l - \ \{\#a\# \})$ *then Some a else None*
 | - \Rightarrow *None*)

definition *is-unit-clause-code* :: *'a literal list* \Rightarrow (*'a, 'b*) *ann-lits*

\Rightarrow *'a literal option* **where**

is-unit-clause-code *l M* =

(*case List.filter* ($\lambda a. \text{atm-of } a \notin \text{atm-of ' lits-of-l } M$) *l of*
 a # [] \Rightarrow *if* ($\forall c \in \text{set } (\text{remove1 } a \ l). -c \in \text{lits-of-l } M$) *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:  $\bigwedge a. (\forall c \in \text{set } (\text{remove1 } a \ l). - c \in \text{lits-of-}l \ M) \longleftrightarrow M \models_{as} CNot \ (mset \ l - \{\#a\# \})$ 
    using lits-of-l-unfold[of remove1 - l, of - M] by simp
  then show ?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 ← l . atm-of a  $\notin$  atm-of ‘lits-of-l M’] of []  $\Rightarrow$  None
    | [a]  $\Rightarrow$  if  $M \models_{as} CNot \ (mset \ l - \{\#a\# \})$  then Some a else None
    | a # ab # xa  $\Rightarrow$  Map.empty xa) = Some a
    using assms unfolding is-unit-clause-def .
  then have a  $\in$  set [a ← l . atm-of a  $\notin$  atm-of ‘lits-of-l M’]
    apply (cases [a ← l . atm-of a  $\notin$  atm-of ‘lits-of-l M’])
    apply simp
    apply (rename-tac aa list; case-tac list) by (auto split: if-split-asm)
  then have atm-of a  $\notin$  atm-of ‘lits-of-l M’ by auto
  then show ?thesis
    by (simp add: Decided-Propagated-in-iff-in-lits-of-l
      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  $\models_{as}$  CNot (mset l - {#a#})
  unfolding is-unit-clause-def
proof –
  assume (case [a ← l . atm-of a  $\notin$  atm-of ‘lits-of-l M’] of []  $\Rightarrow$  None
    | [a]  $\Rightarrow$  if  $M \models_{as} CNot \ (mset \ l - \{\#a\# \})$  then Some a else None
    | a # ab # xa  $\Rightarrow$  Map.empty xa) = Some a
  then show ?thesis
    apply (cases [a ← l . atm-of a  $\notin$  atm-of ‘lits-of-l M’], simp)
    apply simp
    apply (rename-tac aa list; case-tac list) by (auto split: if-split-asm)
qed

lemma is-unit-clause-some-in: is-unit-clause l M = Some a  $\implies$  a  $\in$  set l
  unfolding is-unit-clause-def
proof –
  assume (case [a ← l . atm-of a  $\notin$  atm-of ‘lits-of-l M’] of []  $\Rightarrow$  None
    | [a]  $\Rightarrow$  if  $M \models_{as} CNot \ (mset \ l - \{\#a\# \})$  then Some a else None
    | a # ab # xa  $\Rightarrow$  Map.empty xa) = Some a
  then show a  $\in$  set l
    by (cases [a ← l . atm-of a  $\notin$  atm-of ‘lits-of-l M’]
      (fastforce dest: filter-eq-ConsD split: if-split-asm split: list.splits))+
qed

lemma is-unit-clause-Nil[simp]: is-unit-clause [] M = None
  unfolding is-unit-clause-def by auto

```

Unit propagation for all clauses

Finding the first clause to propagate

fun *find-first-unit-clause* :: '*a* literal list list \Rightarrow ('*a*, '*b*) ann-lits

$\Rightarrow ('a \text{ literal} \times 'a \text{ literal list}) \text{ option}$ **where**
 $\text{find-first-unit-clause } (a \# l) M =$
 $(\text{case is-unit-clause } a M \text{ of}$
 $\quad \text{None} \Rightarrow \text{find-first-unit-clause } l M$
 $\quad | \text{Some } L \Rightarrow \text{Some } (L, a)) |$
 $\text{find-first-unit-clause } [] = \text{None}$

lemma *find-first-unit-clause-some*:
 $\text{find-first-unit-clause } l M = \text{Some } (a, c)$
 $\implies c \in \text{set } l \wedge M \models_{\text{as}} \text{CNot } (\text{mset } c - \{\#a\# \}) \wedge \text{undefined-lit } M a \wedge a \in \text{set } c$
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 ∈ set c
shows $\text{is-unit-clause } c M \neq \text{None}$

proof –
have $[a \leftarrow c . \text{atm-of } a \notin \text{atm-of ' lits-of-l } M] = [a]$
using *assms*
proof (*induction c*)
case Nil then show ?case by simp
next
case (Cons ac c)
show ?case
proof (*cases a = ac*)
case True
then show ?thesis using Cons
by (*auto simp del: lits-of-l-unfold*
 $\text{simp add: lits-of-l-unfold[symmetric] Decided-Propagated-in-iff-in-lits-of-l}$
 $\text{atm-of-eq-atm-of atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set}$)
next
case False
then have $T: \text{mset } c + \{\#ac\# \} - \{\#a\# \} = \text{mset } c - \{\#a\# \} + \{\#ac\# \}$
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
then show ?thesis
using M unfolding is-unit-clause-def by auto
qed

lemma *find-first-unit-clause-none*:
 $\text{distinct } c \implies c \in \text{set } l \implies M \models_{\text{as}} \text{CNot } (\text{mset } c - \{\#a\# \}) \implies \text{undefined-lit } M a \implies a \in \text{set } c$
 $\implies \text{find-first-unit-clause } l M \neq \text{None}$
by (*induction l*)
 $(\text{auto split: option.split simp add: propagate-is-unit-clause-not-None})$

Decide

fun *find-first-unused-var* :: $'a \text{ literal list list} \Rightarrow 'a \text{ literal set} \Rightarrow 'a \text{ literal option}$ **where**

find-first-unused-var ($a \# l$) $M =$
 (case *List.find* ($\lambda lit. lit \notin M \wedge \neg lit \notin M$) a of
 None \Rightarrow *find-first-unused-var* l M
 | Some $a \Rightarrow$ Some a) |
find-first-unused-var [] = None

lemma *find-none*[*iff*]:
List.find ($\lambda lit. lit \notin M \wedge \neg lit \notin M$) $a = \text{None} \longleftrightarrow \text{atm-of ' set } a \subseteq \text{atm-of ' } M$
apply (*induct* a)
using *atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set*
by (*force simp add: atm-of-in-atm-of-set-iff-in-set-or-uminus-in-set*) +

lemma *find-some*: *List.find* ($\lambda lit. lit \notin M \wedge \neg lit \notin M$) $a = \text{Some } b \implies b \in \text{set } a \wedge b \notin M \wedge \neg b \notin M$
unfolding *find-Some-iff* **by** (*metis nth-mem*)

lemma *find-first-unused-var-None*[*iff*]:
find-first-unused-var l $M = \text{None} \longleftrightarrow (\forall a \in \text{set } l. \text{atm-of ' set } a \subseteq \text{atm-of ' } M)$
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 $M = \text{Some } c$
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 $M \neq \text{None}$
using *assms* **by** (*cases find-first-unused-var* l M) *auto*
then show $\neg(\forall a \in \text{set } l. \text{atm-of ' set } a \subseteq \text{atm-of ' } M)$ **by** *auto*
qed

lemma *find-first-unused-var-Some*:
find-first-unused-var l $M = \text{Some } a \implies (\exists m \in \text{set } l. a \in \text{set } m \wedge a \notin M \wedge \neg a \notin M)$
by (*induct* l) (*auto split: option.splits dest: find-some*)

lemma *find-first-unused-var-undefined*:
find-first-unused-var l (*lits-of-l* M s) = Some $a \implies \text{undefined-lit } M$ s a
using *find-first-unused-var-Some*[*of l lits-of-l Ms a*] *Decided-Propagated-in-iff-in-lits-of-l*
by *blast*

7.1.2 CDCL specific functions

Level

fun *maximum-level-code*:: 'a literal list \Rightarrow ('a, 'b) ann-lits \Rightarrow nat
where
maximum-level-code [] = 0 |
maximum-level-code ($L \# L$ s) $M = \max (\text{get-level } M$ L) (*maximum-level-code* L s M)

lemma *maximum-level-code-eq-get-maximum-level*[*simp*]:
maximum-level-code D $M = \text{get-maximum-level } M$ (*mset* D)
by (*induction* D) (*auto simp add: get-maximum-level-plus*)

lemma [*code*]:
fixes $M :: ('a, 'b) \text{ann-lits}$
shows *get-maximum-level* M (*mset* D) = *maximum-level-code* D M
by *simp*

Backjumping

fun *find-level-decomp* **where**

find-level-decomp $M \ [] \ D \ k = \text{None} \mid$

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* $M \ Ls \ D \ k = \text{Some} \ (L, j)$

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** $IH = \text{this}(1)$ **and** $H = \text{this}(2)$

def *find* \equiv (*if* *get-level* $M \ L' \neq k \vee \neg \text{get-maximum-level } M \ (\text{mset } D + \text{mset } Ls) < \text{get-level } M \ L'$

then *find-level-decomp* $M \ Ls \ (L' \ \# \ D) \ k$

else *Some* ($L', \text{get-maximum-level } M \ (\text{mset } D + \text{mset } Ls)$))

have $a1: \bigwedge D. \text{find-level-decomp } M \ Ls \ D \ k = \text{Some} \ (L, j) \Rightarrow$

$L \in \text{set } Ls \wedge \text{get-maximum-level } M \ (\text{mset } Ls + \text{mset } D - \{\#L\# \}) = j \wedge \text{get-level } M \ L = k$

using IH **by** *simp*

have $a2: \text{find} = \text{Some} \ (L, j)$

using H **unfolding** *find-def* **by** (*auto split: if-split-asm*)

{ **assume** *Some* ($L', \text{get-maximum-level } M \ (\text{mset } D + \text{mset } Ls)$) $\neq \text{find}$

then have $f3: L \in \text{set } Ls$ **and** *get-maximum-level* $M \ (\text{mset } Ls + \text{mset } (L' \ \# \ D) - \{\#L\# \}) = j$

using $a1 \ a2$ **unfolding** *find-def* **by** *meson+*

moreover then have $\text{mset } Ls + \text{mset } D - \{\#L\# \} + \{\#L'\# \} = \{\#L'\# \} + \text{mset } D + (\text{mset } Ls - \{\#L\# \})$

by (*auto simp: ac-simps multiset-eq-iff Suc-leI*)

ultimately have $f4: \text{get-maximum-level } M \ (\text{mset } Ls + \text{mset } D - \{\#L\# \} + \{\#L'\# \}) = j$

by (*metis add.commute diff-union-single-conv in-multiset-in-set mset.simps(2)*)

} **note** $f4 = \text{this}$

have $\{\#L'\# \} + (\text{mset } Ls + \text{mset } D) = \text{mset } Ls + (\text{mset } D + \{\#L'\# \})$

by (*auto simp: ac-simps*)

then have

$L = L' \longrightarrow \text{get-maximum-level } M \ (\text{mset } Ls + \text{mset } D) = j \wedge \text{get-level } M \ L' = k$ **and**

$L \neq L' \longrightarrow L \in \text{set } Ls \wedge \text{get-maximum-level } M \ (\text{mset } Ls + \text{mset } D - \{\#L\# \} + \{\#L'\# \}) = j \wedge \text{get-level } M \ L = k$

using $a2 \ a1[\text{of } L' \ \# \ D]$ **unfolding** *find-def* **apply** (*metis add-diff-cancel-left' mset.simps(2) option.inject prod.inject union-commute*)

using $f4 \ a2 \ a1[\text{of } L' \ \# \ D]$ **unfolding** *find-def* **by** (*metis option.inject prod.inject*)

then show ?*case* **by** *simp*

qed

lemma *find-level-decomp-none*:

assumes *find-level-decomp* $M \ Ls \ E \ k = \text{None}$ **and** $\text{mset } (L \ \# \ D) = \text{mset } (Ls \ @ \ E)$

shows $\neg(L \in \text{set } Ls \wedge \text{get-maximum-level } M \ (\text{mset } D) < k \wedge k = \text{get-level } M \ L)$

using *assms*

proof (*induction* Ls *arbitrary*: $E \ L \ D$)

case *Nil*

then show ?*case* **by** *simp*

next

```

case (Cons L' Ls) note IH = this(1) and find-none = this(2) and LD = this(3)
have mset D + {#L'#} = mset E + (mset Ls + {#L'#})  $\implies$  mset D = mset E + mset Ls
  by (metis add-right-imp-eq union-assoc)
then show ?case
  using find-none IH[of L' # E L D] LD by (auto simp add: ac-simps split: if-split-asm)
qed

```

fun bt-cut **where**

```

bt-cut i (Propagated - - # Ls) = bt-cut i Ls |
bt-cut i (Decided K # Ls) = (if count-decided Ls = i then Some (Decided K # Ls) else bt-cut i Ls) |
bt-cut i [] = None

```

lemma bt-cut-some-decomp:

```

assumes no-dup M and bt-cut i M = Some M'
shows  $\exists K M2 M1. M = M2 @ M' \wedge M' = \text{Decided } K \# M1 \wedge \text{get-level } M K = (i+1)$ 
using assms by (induction i M rule: bt-cut.induct) (auto split: if-split-asm)

```

lemma bt-cut-not-none:

```

assumes no-dup M and M = M2 @ Decided K # M' and get-level M K = (i+1)
shows bt-cut i M  $\neq$  None
using assms by (induction M2 arbitrary: M rule: ann-lit-list-induct)
(auto simp: atm-lit-of-set-lits-of-l)

```

lemma get-all-ann-decomposition-ex:

```

 $\exists N. (\text{Decided } K \# M', N) \in \text{set } (\text{get-all-ann-decomposition } (M2 @ \text{Decided } K \# M'))$ 
apply (induction M2 rule: ann-lit-list-induct)
apply auto[2]
by (rename-tac L m xs, case-tac get-all-ann-decomposition (xs @ Decided K # M'))
auto

```

lemma bt-cut-in-get-all-ann-decomposition:

```

assumes no-dup M and bt-cut i M = Some M'
shows  $\exists M2. (M', M2) \in \text{set } (\text{get-all-ann-decomposition } M)$ 
using bt-cut-some-decomp[OF assms] by (auto simp add: get-all-ann-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 (Decided - # Ls)  $\Rightarrow$  (Propagated L D # Ls, N, D # U, j, None)
    | -  $\Rightarrow$  (M, N, U, k, Some D))
  ) |
do-backtrack-step S = S

```

end

theory DPLL-W-Implementation

imports DPLL-CDCL-W-Implementation DPLL-W $\sim\sim$ /src/HOL/Library/Code-Target-Numeral

begin

7.1.3 Simple Implementation of DPLL

Combining the propagate and decide: a DPLL step

definition DPLL-step :: int dpll_W-ann-lits \times int literal list list

```

⇒ int dpllW-ann-lits × int literal list list where
DPLL-step = (λ(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-l 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-l Ms) of
        Some a ⇒ (Decided a # Ms, N)
      | None ⇒ (Ms, N))))

```

Example of propagation:

```

value DPLL-step ([Decided (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) ann-lits)
  (N:: int literal list list). (Ms, mset (map mset N))
abbreviation toS' ≡ λ(Ms::(int, unit) ann-lits,
  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 neq: (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)
  then have 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⟩ by (auto simp add: C)
  then have ?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 neq unfolding DPLL-step-def prod.case unit
    by (cases backtrack-split Ms, rename-tac b, case-tac b) auto

```

```

then have is-decided L using backtrack-split-snd-hd-decided[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-decided 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-l Ms) = Some L
    using step exC neq unfolding DPLL-step-def prod.case unit
    by (cases find-first-unused-var N (lits-of-l Ms)) auto
  have dpllW (Ms, mset (map mset N))
    (Decided 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: Decided-Propagated-in-iff-in-lits-of-l atms-of-ms-def)
  moreover have (Ms', N') = (Decided 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-dpllW-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)
  then have 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) = []

```

```

  then show 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

```

```

  then have Ms: Ms = Propagated (¬ lit-of aa) () # list using Ms by auto

```

```

  have is-decided aa using backtrack-split-snd-hd-decided[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

```

```

  then show snd (backtrack-split Ms) = [] by blast

```

```

qed

```

```

then have ?thesis
  using n backtrack-snd-empty-not-decided[of Ms] unfolding conclusive-dpllW-state-def
  by (cases backtrack-split Ms) auto
}
moreover {
  assume n:  $\neg (\exists C \in \text{set } N. Ms \models_{as} CNot (mset C))$ 
  then have find-first-unused-var N (lits-of-l Ms) = None
    using step unfolding DPLL-step-def by (simp add: unit split: option.splits)
  then have a:  $\forall a \in \text{set } N. atm\text{-of } 'set\ a \subseteq atm\text{-of } '(lits\text{-of-l } Ms)$  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:  $x \in \text{set-mset } (clauses (toS Ms N))$ 
    then have  $\neg Ms \models_{as} CNot\ x$  using n unfolding true-annots-def CNot-def Ball-def by auto
    moreover have total-over-m (lits-of-l 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-l Ms x] by (simp add: true-annot-def true-annots-true-cls)
    qed
  then have ?thesis unfolding conclusive-dpllW-state-def by blast
}
ultimately show ?thesis by blast
qed

```

Adding invariants

Invariant tested in the function `function DPLL-ci :: int dpllW-ann-lits \Rightarrow int literal list list \Rightarrow int dpllW-ann-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-ann-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)
then show ((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-ann-lits \Rightarrow int literal list list \Rightarrow int dpllW-ann-lits \times int literal list list where`

```

DPLL-part Ms N =
  (let (Ms', N') = DPLL-step (Ms, N) in
  if (Ms', N') = (Ms, N) then (Ms, N) else DPLL-part Ms' N)

```

by *fast+*

lemma *snd-DPLL-step[simp]*:
 $\text{snd } (DPLL\text{-step } (Ms, N)) = N$
unfolding *DPLL-step-def* **by** (*auto split: if-split option.splits prod.splits list.splits*)

lemma *dpll_W-all-inv-implieS-2-eq3-and-dom*:
assumes *dpll_W-all-inv* (*Ms, mset (map mset N)*)
shows *DPLL-ci* *Ms N* = *DPLL-part* *Ms N* \wedge *DPLL-part-dom* (*Ms, N*)
using *assms*

proof (*induct rule: DPLL-ci.induct*)
case (*1 Ms N*)
have $\text{snd } (DPLL\text{-step } (Ms, N)) = N$ **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*)
then have *DPLL-ci* *Ms' N* = *DPLL-part* *Ms' N* \wedge *DPLL-part-dom* (*Ms', N*) **using** *1(1)[of - Ms' N]* *Ms'*
1(2) inv' **by** *auto*
then have *DPLL-part-dom* (*Ms, N*) **using** *DPLL-part.domintros Ms'* **by** *fastforce*
moreover have *DPLL-ci* *Ms N* = *DPLL-part* *Ms N* **using** *1.prem DPLL-part.psimps Ms'*
 $\langle DPLL\text{-ci } Ms' N = DPLL\text{-part } Ms' N \wedge DPLL\text{-part-dom } (Ms', N) \rangle \langle DPLL\text{-part-dom } (Ms, N) \rangle$ **by** *auto*
ultimately have *?case* **by** *blast*
}
moreover {
assume (*Ms', N*) = (*Ms, N*)
then have *?case* **using** *DPLL-part.domintros DPLL-part.psimps Ms'* **by** *fastforce*
}
ultimately show *?case* **by** *blast*
qed

lemma *DPLL-ci-dpll_W-rtrancp*:
assumes *DPLL-ci* *Ms N* = (*Ms', N'*)
shows *dpll_W*** (*toS Ms N*) (*toS Ms' N*)
using *assms*

proof (*induct Ms N arbitrary: Ms' N' rule: DPLL-ci.induct*)
case (*1 Ms N Ms' N'*) **note** *IH* = *this(1)* **and** *step* = *this(2)*
obtain *S₁ S₂* **where** *S*: (*S₁, S₂*) = *DPLL-step* (*Ms, N*) **by** (*cases DPLL-step (Ms, N)*) *auto*

{ assume $\neg dpll_W\text{-all-inv } (toS Ms N)$
then have (*Ms, N*) = (*Ms', N*) **using** *step* **by** *auto*
then have *?case* **by** *auto*
}
moreover
{ assume *dpll_W-all-inv* (*toS Ms N*)
and (*S₁, S₂*) = (*Ms, N*)
then have *?case* **using** *S step* **by** *auto*
}
moreover
{ assume *dpll_W-all-inv* (*toS Ms N*)
and (*S₁, S₂*) \neq (*Ms, N*)
moreover obtain *S₁' S₂'* **where** *DPLL-ci* *S₁ N* = (*S₁', S₂'*) **by** (*cases DPLL-ci S₁ N*) *auto*
moreover have *DPLL-ci* *Ms N* = *DPLL-ci* *S₁ N* **using** *DPLL-ci.simps[of Ms N]* *calculation*
proof –


```

have (case (S1, S2) of (ms, lss) ⇒
  if (ms, lss) = (Ms, N) then (Ms, N) else DPLL-ci ms N) = DPLL-ci Ms N
  using S DPLL-ci.simps[of Ms N] calculation by presburger
then have (if (S1, S2) = (Ms, N) then (Ms, N) else DPLL-ci S1 N) = DPLL-ci Ms N
  by fastforce
then show ?thesis
  using calculation(2) by presburger
qed
ultimately have dpllW** (toS S1' N) (toS Ms' N) using IH[of (S1, S2) S1 S2] S step by simp

moreover have dpllW (toS Ms N) (toS S1 N)
  by (metis DPLL-step-is-a-dpllW-step S ⟨(S1, S2) ≠ (Ms, N)⟩ prod.sel(2) snd-DPLL-step)
ultimately have ?case by (metis (mono-tags, hide-lams) IH S ⟨(S1, S2) ≠ (Ms, N)⟩
  ⟨DPLL-ci Ms N = DPLL-ci S1 N⟩ ⟨dpllW-all-inv (toS Ms N)⟩ converse-rtranclp-into-rtranclp
  local.step)
}
ultimately show ?case by blast
qed

lemma dpllW-all-inv-dpllW-tranclp-irrefl:
  assumes dpllW-all-inv (Ms, N)
  and dpllW++ (Ms, N) (Ms, N)
  shows False
proof –
  have 1: wf {(S', S). dpllW-all-inv S ∧ dpllW++ S S'} using dpllW-wf-tranclp by auto
  have ((Ms, N), (Ms, N)) ∈ {(S', S). dpllW-all-inv S ∧ dpllW++ S S'} using assms by auto
  then show False using wf-not-refl[OF 1] by blast
qed

lemma DPLL-ci-final-state:
  assumes step: DPLL-ci Ms N = (Ms, N)
  and inv: dpllW-all-inv (toS Ms N)
  shows conclusive-dpllW-state (toS Ms N)
proof –
  have st: dpllW** (toS Ms N) (toS Ms N) using DPLL-ci-dpllW-rtranclp[OF step] .
  have DPLL-step (Ms, N) = (Ms, N)
  proof (rule ccontr)
    obtain Ms' N' where Ms'N': (Ms', N') = DPLL-step (Ms, N)
    by (cases DPLL-step (Ms, N)) auto
    assume ¬ ?thesis
    then have DPLL-ci Ms' N = (Ms, N) using step inv st Ms'N'[symmetric] by fastforce
    then have dpllW++ (toS Ms N) (toS Ms N)
    by (metis DPLL-ci-dpllW-rtranclp DPLL-step-is-a-dpllW-step Ms'N' ⟨DPLL-step (Ms, N) ≠ (Ms,
N)⟩
      prod.sel(2) rtranclp-into-tranclp2 snd-DPLL-step)
    then show False using dpllW-all-inv-dpllW-tranclp-irrefl inv by auto
  qed
  then show ?thesis using DPLL-step-stuck-final-state[of Ms N] by simp
qed

lemma DPLL-step-obtains:
  obtains Ms' where (Ms', N) = DPLL-step (Ms, N)
  unfolding DPLL-step-def by (metis (no-types, lifting) DPLL-step-def prod.collapse snd-DPLL-step)

lemma DPLL-ci-obtains:
  obtains Ms' where (Ms', N) = DPLL-ci Ms N

```

proof (*induct rule: DPLL-ci.induct*)
case ($1 \text{ } Ms \text{ } N$) **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
 $\{ \text{assume } \neg \text{dpll}_W\text{-all-inv } (\text{toS } Ms \text{ } N)$
 $\text{then have } ?case \text{ using } \text{that} \text{ by } \text{auto}$
 $\}$
moreover $\{$
 $\text{assume } n: (S, N) \neq (Ms, N)$
 $\text{and } \text{inv}: \text{dpll}_W\text{-all-inv } (\text{toS } Ms \text{ } N)$
 $\text{have } \exists ms. \text{DPLL-step } (Ms, N) = (ms, N)$
 $\text{by } (\text{metis } \langle \bigwedge \text{thesis}. (\bigwedge S. (S, N) = \text{DPLL-step } (Ms, N) \implies \text{thesis}) \implies \text{thesis} \rangle)$
 $\text{then have } ?thesis$
 $\text{using } IH \text{ that by } \text{fastforce}$
 $\}$
moreover $\{$
 $\text{assume } n: (S, N) = (Ms, N)$
 $\text{then have } ?case \text{ using } SN \text{ that by } \text{fastforce}$
 $\}$
ultimately show $?case$ **by** blast
qed

lemma $\text{DPLL-ci-no-more-step}$:

assumes $\text{step}: \text{DPLL-ci } Ms \text{ } N = (Ms', N')$
shows $\text{DPLL-ci } Ms' \text{ } N' = (Ms', N')$
using assms

proof (*induct arbitrary: $Ms' \text{ } N'$ rule: DPLL-ci.induct*)
case ($1 \text{ } Ms \text{ } N \text{ } Ms' \text{ } N'$) **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
 $\{ \text{assume } \neg \text{dpll}_W\text{-all-inv } (\text{toS } Ms \text{ } N)$
 $\text{then have } ?case \text{ using } \text{step} \text{ by } \text{auto}$
 $\}$
moreover $\{$
 $\text{assume } \text{dpll}_W\text{-all-inv } (\text{toS } Ms \text{ } N)$
 $\text{and } (S_1, N) = (Ms, N)$
 $\text{then have } ?case \text{ using } S \text{ step by } \text{auto}$
 $\}$
moreover
 $\{ \text{assume } \text{inv}: \text{dpll}_W\text{-all-inv } (\text{toS } Ms \text{ } N)$
 $\text{assume } n: (S_1, N) \neq (Ms, N)$
 $\text{obtain } S_1' \text{ where } SS: (S_1', N) = \text{DPLL-ci } S_1 \text{ } N \text{ using } \text{DPLL-ci-obtains by blast}$
 $\text{moreover have } \text{DPLL-ci } Ms \text{ } N = \text{DPLL-ci } S_1 \text{ } N$
 proof -
 $\text{have } (\text{case } (S_1, N) \text{ of } (ms, lss) \Rightarrow \text{if } (ms, lss) = (Ms, N) \text{ then } (Ms, N) \text{ else } \text{DPLL-ci } ms \text{ } N)$
 $= \text{DPLL-ci } Ms \text{ } N$
 $\text{using } S \text{ DPLL-ci.simps[of } Ms \text{ } N] \text{ calculation inv by presburger}$
 $\text{then have } (\text{if } (S_1, N) = (Ms, N) \text{ then } (Ms, N) \text{ else } \text{DPLL-ci } S_1 \text{ } N) = \text{DPLL-ci } Ms \text{ } N$
 by fastforce
 $\text{then show } ?thesis$
 $\text{using calculation n by presburger}$
 qed
moreover
 $\text{have } \text{DPLL-ci } S_1' \text{ } N = (S_1', N) \text{ using step IH[OF - - S n SS[symmetric]] inv by blast}$
 $\text{ultimately have } ?case \text{ using step by fastforce}$
 $\}$
ultimately show $?case$ **by** blast

qed

lemma *DPLL-part-dpll_W-all-inv-final*:

fixes *M Ms':: (int, unit) ann-lits 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) ∧ 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-implieS-2-eq3-and-dom by blast*

then have *star: dpll_W** (toS Ms N) (toS Ms' N) unfolding MsN using DPLL-ci-dpll_W-rtrancpl*

by blast

then have *inv': dpll_W-all-inv (toS Ms' N) using inv rtrancpl-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) ann-lits, N::int literal list list).

dpll_W-all-inv (toS M N))}

morphisms *rough-state-of state-of*

proof

show *([],[]) ∈ {(M, N). dpll_W-all-inv (toS M N)} by (auto simp add: dpll_W-all-inv-def)*

qed

lemma

DPLL-part-dom ([], N)

using *dpll_W-all-inv-implieS-2-eq3-and-dom[of [] 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 ⇒ dpll_W-state ⇒ 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 ⇒ dpll_W-state where*

DPLL-step' S = state-of (DPLL-step (rough-state-of S))

declare *rough-state-of-inverse[simp]*

lemma *DPLL-step-dpll_W-conc-inv:*

DPLL-step (rough-state-of S) ∈ {(M, N). dpll_W-all-inv (toS M N)}

by *(smt DPLL-ci.simps DPLL-ci-dpll_W-rtrancpl case-prodE case-prodI2 rough-state-of*

mem-Collect-eq old.prod.case prod.sel(2) rtrancpl-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-dpll_W-conc-inv DPLL-step'-def state-of-inverse by auto*

function *DPLL-tot:: dpll_W-state ⇒ dpll_W-state where*

$DPLL\text{-}tot\ S =$
 (let $S' = DPLL\text{-}step'\ S$ in
 if $S' = S$ then S else $DPLL\text{-}tot\ S'$)
 by fast+
termination
proof (relation $\{(T', T)\}$.
 (rough-state-of T' , rough-state-of T)
 $\in \{(S', S). (toS'\ S', toS'\ S)\}$
 $\in \{(S', S). dpll_W\text{-}all\text{-}inv\ S \wedge dpll_W\ S\ S'\}\})$
show wf $\{(b, a)\}$.
 (rough-state-of b , rough-state-of a)
 $\in \{(b, a). (toS'\ b, toS'\ a)\}$
 $\in \{(b, a). dpll_W\text{-}all\text{-}inv\ a \wedge dpll_W\ a\ b\}\}$
 using wf-if-measure-f[OF wf-if-measure-f[OF $dpll_W\text{-}wf$, of toS'], of rough-state-of] .
next
fix $S\ x$
assume $x: x = DPLL\text{-}step'\ S$
and $x \neq S$
have $dpll_W\text{-}all\text{-}inv$ (case rough-state-of S of $(Ms, N) \Rightarrow (Ms, mset\ (map\ mset\ N))$)
 by (metis (no-types, lifting) case-prodE mem-Collect-eq old.prod.case rough-state-of)
moreover have $dpll_W$ (case rough-state-of S of $(Ms, N) \Rightarrow (Ms, mset\ (map\ mset\ N))$)
 (case rough-state-of $(DPLL\text{-}step'\ S)$ of $(Ms, N) \Rightarrow (Ms, mset\ (map\ mset\ N))$)
proof –
obtain $Ms\ N$ **where** $Ms: (Ms, N) = \text{rough-state-of}\ S$ **by** (cases rough-state-of S) **auto**
have $dpll_W\text{-}all\text{-}inv$ ($toS'\ (Ms, N)$) **using** calculation **unfolding** Ms **by** blast
moreover obtain $Ms'\ N'$ **where** $Ms': (Ms', N') = \text{rough-state-of}\ (DPLL\text{-}step'\ S)$
 by (cases rough-state-of $(DPLL\text{-}step'\ S)$) **auto**
ultimately have $dpll_W\text{-}all\text{-}inv$ ($toS'\ (Ms', N')$) **unfolding** Ms'
 by (metis (no-types, lifting) case-prod-unfold mem-Collect-eq rough-state-of)

have $dpll_W$ ($toS\ Ms\ N$) ($toS\ Ms'\ N'$)
 apply (rule $DPLL\text{-}step\text{-}is\text{-}a\text{-}dpll_W\text{-}step$ [of $Ms'\ N'\ Ms\ N$])
 unfolding $Ms\ Ms'$ **using** $\langle x \neq S \rangle$ rough-state-of-inject x **by** fastforce+
then show ?thesis **unfolding** Ms [symmetric] Ms' [symmetric] **by** auto
qed
ultimately show $(x, S) \in \{(T', T). (\text{rough-state-of}\ T', \text{rough-state-of}\ T)\}$
 $\in \{(S', S). (toS'\ S', toS'\ S) \in \{(S', S). dpll_W\text{-}all\text{-}inv\ S \wedge dpll_W\ S\ S'\}\}\}$
by (auto simp add: x)
qed

lemma [code]:

$DPLL\text{-}tot\ S =$
 (let $S' = DPLL\text{-}step'\ S$ in
 if $S' = S$ then S else $DPLL\text{-}tot\ S'$) **by** auto

lemma $DPLL\text{-}tot\text{-}DPLL\text{-}step\text{-}DPLL\text{-}tot$ [simp]: $DPLL\text{-}tot\ (DPLL\text{-}step'\ S) = DPLL\text{-}tot\ S$
apply (cases $DPLL\text{-}step'\ S = S$)
apply simp
unfolding $DPLL\text{-}tot.simps$ [of S] **by** (simp del: $DPLL\text{-}tot.simps$)

lemma $DOPLL\text{-}step'\text{-}DPLL\text{-}tot$ [simp]:

$DPLL\text{-}step'\ (DPLL\text{-}tot\ S) = DPLL\text{-}tot\ S$
by (rule $DPLL\text{-}tot.induct$ [of $\lambda S. DPLL\text{-}step'\ (DPLL\text{-}tot\ S) = DPLL\text{-}tot\ S$])
 (metis (full-types) $DPLL\text{-}tot.simps$)

lemma *DPLL-tot-final-state*:
assumes *DPLL-tot* $S = S$
shows *conclusive-dpll_W-state* (*toS'* (*rough-state-of* S))
proof –
have *DPLL-step'* $S = S$ **using** *assms*[*symmetric*] *DOPLL-step'-DPLL-tot* **by** *metis*
then have *DPLL-step* (*rough-state-of* S) = (*rough-state-of* S)
unfolding *DPLL-step'-def* **using** *DPLL-step-dpll_W-conc-inv* *rough-state-of-inverse*
by (*metis* *rough-state-of-DPLL-step'-DPLL-step*)
then show *?thesis*
by (*metis* (*mono-tags*, *lifting*) *DPLL-step-stuck-final-state* *old.prod.exhaust* *split-conv*)
qed

lemma *DPLL-tot-star*:
assumes *rough-state-of* (*DPLL-tot* S) = S'
shows *dpll_W*** (*toS'* (*rough-state-of* S)) (*toS'* S')
using *assms*
proof (*induction arbitrary: S' rule: DPLL-tot.induct*)
case (1 $S S'$)
let $?x = \text{DPLL-step}' S$
{ assume $?x = S$
then have *?case* **using** 1(2) **by** *simp*
}
moreover {
assume $S: ?x \neq S$
have *?case*
apply (*cases* *DPLL-step'* $S = S$)
using S **apply** *blast*
by (*smt* 1.IH 1.prem *DPLL-step-is-a-dpll_W-step* *DPLL-tot.simps* *case-prodE2*
rough-state-of-DPLL-step'-DPLL-step *rtranclp.rtrancl-into-rtrancl* *rtranclp.rtrancl-refl*
rtranclp-idemp *split-conv*)
}
ultimately show *?case* **by** *auto*
qed

lemma *rough-state-of-rough-state-of-Nil*[*simp*]:
rough-state-of (*state-of* (\square , N)) = (\square , N)
apply (*rule* *DPLL-W-Implementation.dpll_W-state.state-of-inverse*)
unfolding *dpll_W-all-inv-def* **by** *auto*

Theorem of correctness

lemma *DPLL-tot-correct*:
assumes *rough-state-of* (*DPLL-tot* (*state-of* (\square , N)))) = (M , N')
and (M' , N'') = *toS'* (M , N')
shows $M' \models_{asm} N'' \longleftrightarrow \text{satisfiable} (\text{set-mset } N'')$
proof –
have *dpll_W*** (*toS'* (\square , N)) (*toS'* (M , N'))) **using** *DPLL-tot-star*[*OF* *assms*(1)] **by** *auto*
moreover have *conclusive-dpll_W-state* (*toS'* (M , N')))
using *DPLL-tot-final-state* **by** (*metis* (*mono-tags*, *lifting*) *DOPLL-step'-DPLL-tot* *DPLL-tot.simps*
assms(1))
ultimately show *?thesis* **using** *dpll_W-conclusive-state-correct* **by** (*smt* *DPLL-ci.simps*
DPLL-ci-dpll_W-rtranclp *assms*(2) *dpll_W-all-inv-def* *prod.case* *prod.sel*(1) *prod.sel*(2)
rtranclp-dpll_W-inv(3) *rtranclp-dpll_W-inv-starting-from-0*)
qed

Code export

A conversion to DPLL-W-Implementation. *dpll_W-state* **definition** *Con* :: (*int*, *unit*) *ann-lits* × *int literal list list*

⇒ *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-l* (*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

7.1.4 List-based CDCL Implementation

We here have a very simple implementation of Weidenbach's CDCL, based on the same principle as the implementation of DPLL: iterating over-and-over on lists. We do not use any fancy data-structure (see the two-watched literals for a better suited data-structure).

The goal was (as for DPLL) to test the infrastructure and see if an important lemma was missing to prove the correctness and the termination of a simple implementation.

Types and Instantiation

notation *image-mset* (**infixr** '# 90)

type-synonym '*a cdcl_W-mark* = '*a clause*

type-synonym '*v cdcl_W-ann-lit* = ('*v*, '*v cdcl_W-mark*) *ann-lit*

type-synonym '*v cdcl_W-ann-lits* = ('*v*, '*v cdcl_W-mark*) *ann-lits*

type-synonym '*v cdcl_W-state* =

$'v \text{ cdcl}_W\text{-ann-lits} \times 'v \text{ clauses} \times 'v \text{ clauses} \times \text{nat} \times 'v \text{ clause option}$

abbreviation $\text{raw-trail} :: 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'a$ **where**
 $\text{raw-trail} \equiv (\lambda(M, -). M)$

abbreviation $\text{raw-cons-trail} :: 'a \Rightarrow 'a \text{ list} \times 'b \times 'c \times 'd \times 'e \Rightarrow 'a \text{ list} \times 'b \times 'c \times 'd \times 'e$
where
 $\text{raw-cons-trail} \equiv (\lambda L (M, S). (L \# M, S))$

abbreviation $\text{raw-tl-trail} :: 'a \text{ list} \times 'b \times 'c \times 'd \times 'e \Rightarrow 'a \text{ list} \times 'b \times 'c \times 'd \times 'e$ **where**
 $\text{raw-tl-trail} \equiv (\lambda(M, S). (\text{tl } M, S))$

abbreviation $\text{raw-init-clss} :: 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'b$ **where**
 $\text{raw-init-clss} \equiv \lambda(M, N, -). N$

abbreviation $\text{raw-learned-clss} :: 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'c$ **where**
 $\text{raw-learned-clss} \equiv \lambda(M, N, U, -). U$

abbreviation $\text{raw-backtrack-lvl} :: 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'd$ **where**
 $\text{raw-backtrack-lvl} \equiv \lambda(M, N, U, k, -). k$

abbreviation $\text{raw-update-backtrack-lvl} :: 'd \Rightarrow 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'a \times 'b \times 'c \times 'd \times 'e$
where
 $\text{raw-update-backtrack-lvl} \equiv \lambda k (M, N, U, -, S). (M, N, U, k, S)$

abbreviation $\text{raw-conflicting} :: 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'e$ **where**
 $\text{raw-conflicting} \equiv \lambda(M, N, U, k, D). D$

abbreviation $\text{raw-update-conflicting} :: 'e \Rightarrow 'a \times 'b \times 'c \times 'd \times 'e \Rightarrow 'a \times 'b \times 'c \times 'd \times 'e$
where
 $\text{raw-update-conflicting} \equiv \lambda S (M, N, U, k, -). (M, N, U, k, S)$

abbreviation $S0\text{-cdcl}_W \ N \equiv (([], N, \{\#\}, 0, \text{None})) :: 'v \text{ cdcl}_W\text{-state}$

abbreviation $\text{raw-add-learned-clss}$ **where**
 $\text{raw-add-learned-clss} \equiv \lambda C (M, N, U, S). (M, N, \{\#C\# \} + U, S)$

abbreviation raw-remove-clss **where**
 $\text{raw-remove-clss} \equiv \lambda C (M, N, U, S). (M, \text{removeAll-mset } C \ N, \text{removeAll-mset } C \ U, S)$

lemma raw-trail-conv : $\text{raw-trail } (M, N, U, k, D) = M$ **and**
 clauses-conv : $\text{raw-init-clss } (M, N, U, k, D) = N$ **and**
 $\text{raw-learned-clss-conv}$: $\text{raw-learned-clss } (M, N, U, k, D) = U$ **and**
 $\text{raw-conflicting-conv}$: $\text{raw-conflicting } (M, N, U, k, D) = D$ **and**
 $\text{raw-backtrack-lvl-conv}$: $\text{raw-backtrack-lvl } (M, N, U, k, D) = k$
by *auto*

lemma state-conv :
 $S = (\text{raw-trail } S, \text{raw-init-clss } S, \text{raw-learned-clss } S, \text{raw-backtrack-lvl } S, \text{raw-conflicting } S)$
by (*cases* S) *auto*

interpretation state_W
 raw-trail raw-init-clss raw-learned-clss raw-backtrack-lvl raw-conflicting
 $\lambda L (M, S). (L \# M, S)$
 $\lambda(M, S). (\text{tl } M, S)$

```

λC (M, N, U, S). (M, N, {#C#} + U, S)
λC (M, N, U, S). (M, removeAll-mset C N, removeAll-mset C U, S)
λ(k::nat) (M, N, U, -, D). (M, N, U, k, D)
λD (M, N, U, k, -). (M, N, U, k, D)
λN. ([], N, {#}, 0, None)
by unfold-locales auto

```

interpretation *conflict-driven-clause-learning_W raw-trail raw-init-clss raw-learned-clss raw-backtrack-lvl raw-conflicting*

```

λL (M, S). (L # M, S)
λ(M, S). (tl M, S)
λC (M, N, U, S). (M, N, {#C#} + U, S)
λC (M, N, U, S). (M, removeAll-mset C N, removeAll-mset C U, S)
λ(k::nat) (M, N, U, -, D). (M, N, U, k, D)
λD (M, N, U, k, -). (M, N, U, k, D)
λN. ([], N, {#}, 0, 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]*

lemma *reduce-trail-to-empty-trail[simp]*:
reduce-trail-to F ([], aa, ab, ac, b) = ([], aa, ab, ac, b)
using *reduce-trail-to.simps* **by** *auto*

lemma *raw-trail-reduce-trail-to-length-le*:
assumes *length F > length (raw-trail S)*
shows *raw-trail (reduce-trail-to F S) = []*
using *assms trail-reduce-trail-to-length-le[of S F]*
by (*cases S, cases reduce-trail-to F S*) *auto*

lemma *reduce-trail-to*:
reduce-trail-to F S =
((if length (raw-trail S) ≥ length F
then drop (length (raw-trail S) - length F) (raw-trail S)
else []), raw-init-clss S, raw-learned-clss S, raw-backtrack-lvl S, raw-conflicting S)
(is ?S = -)

proof (*induction F S rule: reduce-trail-to.induct*)
case (*1 F S*) **note** *IH = this*
show *?case*
proof (*cases raw-trail S*)
case *Nil*
then show *?thesis* **using** *IH* **by** (*cases S*) *auto*
next
case (*Cons L M*)
then show *?thesis*
apply (*cases Suc (length M) > length F*)
prefer 2 **using** *IH reduce-trail-to-length-ne[of S F]* **apply** (*cases S*) **apply** *auto*
apply (*subgoal-tac Suc (length M) - length F = Suc (length M - length F)*)
using *reduce-trail-to-length-ne[of S F] IH* **by** (*cases S*) *auto*
qed
qed

7.1.5 CDCL Implementation

Definition of the rules

Types lemma *true-raw-init-clss-remdups*[simp]:
 $I \models_s (mset \circ remdups) \text{ ' } N \longleftrightarrow I \models_s mset \text{ ' } N$
 by (simp add: true-clss-def)

lemma *satisfiable-mset-remdups*[simp]:
 $satisfiable ((mset \circ remdups) \text{ ' } N) \longleftrightarrow satisfiable (mset \text{ ' } N)$
 unfolding *satisfiable-carac*[symmetric] by simp

type-synonym *'v cdcl_W-state-inv-st* = (*'v*, *'v literal list*) *ann-lit list* ×
'v literal list list × *'v literal list list* × *nat* × *'v literal list option*

We need some functions to convert between our abstract state *'v cdcl_W-state* and the concrete state *'v cdcl_W-state-inv-st*.

fun *convert* :: (*'a*, *'c list*) *ann-lit* ⇒ (*'a*, *'c multiset*) *ann-lit* **where**
convert (*Propagated L C*) = *Propagated L (mset C)* |
convert (*Decided K*) = *Decided K*

abbreviation *convertC* :: *'a list option* ⇒ *'a multiset option* **where**
convertC ≡ *map-option mset*

lemma *convert-Propagated*[elim!]:
 $convert\ z = Propagated\ L\ C \implies (\exists\ C'.\ z = Propagated\ L\ C' \wedge C = mset\ C')$
 by (cases z) auto

lemma *is-decided-convert*[simp]: *is-decided (convert x) = is-decided x*
 by (cases x) auto

lemma *get-level-map-convert*[simp]:
 $get_level\ (map\ convert\ M)\ x = get_level\ M\ x$
 by (induction M rule: ann-lit-list-induct) (auto simp: comp-def)

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)

Conversion function

fun *toS* :: *'v cdcl_W-state-inv-st* ⇒ *'v 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 *'v cdcl_W-state-inv* = {*S* :: *'v cdcl_W-state-inv-st*. *cdcl_W-all-struct-inv (toS S)*}
morphisms *rough-state-of state-of*
proof
 show (*[]*, *[]*, *[]*, *0*, *None*) ∈ {*S*. *cdcl_W-all-struct-inv (toS S)*}
 by (auto simp add: *cdcl_W-all-struct-inv-def*)
qed

instantiation *cdcl_W-state-inv* :: (*type*) *equal*

begin

definition *equal-cdcl_W-state-inv* :: *'v cdcl_W-state-inv* ⇒ *'v cdcl_W-state-inv* ⇒ *bool* **where**

equal-cdcl_W-state-inv $S S' = (\text{rough-state-of } S = \text{rough-state-of } S')$

instance
 by *standard* (*simp* add: *rough-state-of-inject equal-cdcl_W-state-inv-def*)
 end

lemma *lits-of-map-convert*[*simp*]: *lits-of-l* (*map convert* M) = *lits-of-l* M
 by (*induction* M rule: *ann-lit-list-induct*) *simp-all*

lemma *atm-lit-of-convert*[*simp*]:
lit-of (*convert* x) = *lit-of* x
 by (*cases* x) *auto*

lemma *undefined-lit-map-convert*[*iff*]:
undefined-lit (*map convert* M) $L \longleftrightarrow$ *undefined-lit* $M L$
 by (*auto simp* add: *defined-lit-map image-image*)

lemma *true-annot-map-convert*[*simp*]: *map convert* $M \models_a N \longleftrightarrow M \models_a N$
 by (*simp-all* add: *true-annot-def image-image lits-of-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* ($N @ U$) $M = \text{Some } (L, C)$
 shows *propagate* (*toS* (M, N, U, k, None)) (*toS* (*Propagated* $L C \# M, N, U, k, \text{None}$))
 using *assms*
 by (*auto dest!*: *find-first-unit-clause-some simp* add: *propagate.simps*
intro!: *exI*[*of* - *mset* $C - \{\#L\#$ }\])

The Transitions

Propagate **definition** *do-propagate-step* **where**

do-propagate-step $S =$
 (*case* S of
 (M, N, U, k, None) \Rightarrow
 (*case* *find-first-unit-clause* ($N @ U$) M of
Some (L, C) \Rightarrow (*Propagated* $L C \# M, N, U, k, \text{None}$)
 | *None* \Rightarrow (M, N, U, k, None))
 | $S \Rightarrow S$)

lemma *do-propagate-step*:
do-propagate-step $S \neq S \implies$ *propagate* (*toS* S) (*toS* (*do-propagate-step* S))
apply (*cases* S , *cases raw-conflicting* S)
using *find-first-unit-clause-some-is-propagate*[*of raw-init-clss* S *raw-learned-clss* S *raw-trail* S - -
raw-backtrack-lvl S]
by (*auto simp* add: *do-propagate-step-def split: option.splits*)

lemma *do-propagate-step-option*[*simp*]:
raw-conflicting $S \neq \text{None} \implies$ *do-propagate-step* $S = S$
 unfolding *do-propagate-step-def* by (*cases* S , *cases raw-conflicting* S) *auto*

lemma *do-propagate-step-no-step*:
 assumes *dist*: $\forall c \in \text{set } (\text{raw-init-clss } S @ \text{raw-learned-clss } S). \text{distinct } c$ **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  $M N U k C L E$  where
    toSS:  $toS S = (M, N, U, k, None)$  and
    LE:  $L \in \# E$  and
    T:  $T = (Propagated L E \# M, N, U, k, None)$  and
    MC:  $M \models_{as} CNot C$  and
    undef: undefined-lit  $M L$  and
    CL:  $C + \{\#L\} \in \# N + U$ 
    apply  $-$  by (cases toS S) (auto elim!: propagateE)
  let  $?M = raw-trail S$ 
  let  $?N = raw-init-clss S$ 
  let  $?U = raw-learned-clss S$ 
  let  $?k = raw-backtrack-lvl S$ 
  let  $?D = None$ 
  have  $S: S = (?M, ?N, ?U, ?k, ?D)$ 
    using toSS by (cases S, cases raw-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:  $D \in set (?N @ ?U)$ 
    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 $M (N \# Ns) = (if (\forall c \in set N. \neg c \in lits-of-l M) then Some N else find-conflict M Ns)$

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: if-split-asm)

lemma *find-conflict-None*:

find-conflict $M Ns = None \longleftrightarrow (\forall N \in set Ns. \neg M \models_{as} CNot (mset N))$

by (induction Ns) auto

lemma *find-conflict-None-no-conf*:

find-conflict $M (N @ U) = \text{None} \longleftrightarrow \text{no-step conflict } (\text{toS } (M, N, U, k, \text{None}))$
 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 $a \Rightarrow (M, N, U, k, \text{Some } a)$
 | $\text{None} \Rightarrow (M, N, U, k, \text{None})$)
 | $S \Rightarrow S$)

lemma *do-conflict-step*:

do-conflict-step $S \neq S \implies \text{conflict } (\text{toS } S) (\text{toS } (\text{do-conflict-step } S))$
apply (cases S , cases *raw-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 $S = S \implies \text{no-step conflict } (\text{toS } S)$
apply (cases S , cases *raw-conflicting* S)
unfolding *do-conflict-step-def*
using *find-conflict-None-no-conf*[of *raw-trail* S *raw-init-clss* S *raw-learned-clss* S
raw-backtrack-lvl S]
by (auto split: *option.splits elim!:* *conflictE*)

lemma *do-conflict-step-option[simp]*:

raw-conflicting $S \neq \text{None} \implies \text{do-conflict-step } S = S$
unfolding *do-conflict-step-def* **by** (cases S , cases *raw-conflicting* S) auto

lemma *do-conflict-step-raw-conflicting[dest]*:

do-conflict-step $S \neq S \implies \text{raw-conflicting } (\text{do-conflict-step } S) \neq \text{None}$
unfolding *do-conflict-step-def* **by** (cases S , cases *raw-conflicting* S) (auto split: *option.splits*)

definition *do-cp-step* **where**

do-cp-step $S =$
 (*do-propagate-step* o *do-conflict-step*) S

lemma *cp-step-is-cdcl_W-cp*:

assumes H : *do-cp-step* $S \neq S$
shows *cdcl_W-cp* (*toS* S) (*toS* (*do-cp-step* S))

proof —

show ?thesis

proof (cases *do-conflict-step* $S \neq S$)

case *True*

then show ?thesis

by (auto simp add: *do-conflict-step do-conflict-step-raw-conflicting do-cp-step-def*)

next

case *False*

then have *conf*[*simp*]: *do-conflict-step* $S = S$ **by** *simp*

show ?thesis

proof (cases *do-propagate-step* $S = S$)

case *True*

```

    then show ?thesis
    using H by (simp add: do-cp-step-def)
next
case False
let ?S = toS S
let ?T = toS (do-propagate-step S)
let ?U = toS (do-conflict-step (do-propagate-step S))
have propa: propagate (toS S) ?T using False do-propagate-step by blast
moreover have ns: no-step conflict (toS S) using confl do-conflict-step-no-step by blast
ultimately show ?thesis
    using cdclW-cp.intros(2)[of ?S ?T] confl unfolding do-cp-step-def by auto
qed
qed
qed

```

lemma *do-cp-step-eq-no-prop-no-conf*:
 $do-cp-step\ S = S \implies do-conflict-step\ S = S \wedge do-propagate-step\ S = S$
by (cases S, cases raw-conflicting S)
(auto simp add: do-conflict-step-def do-propagate-step-def do-cp-step-def split: option.splits)

lemma *no-cdcl_W-cp-iff-no-propagate-no-conflict*:
 $no-step\ cdcl_W-cp\ S \longleftrightarrow no-step\ propagate\ S \wedge no-step\ conflict\ S$
by (auto simp: cdcl_W-cp.simps)

lemma *do-cp-step-eq-no-step*:
assumes H: $do-cp-step\ S = S$ **and** $\forall c \in set\ (raw-init-clss\ S @ raw-learned-clss\ S).$ distinct c
shows $no-step\ cdcl_W-cp\ (toS\ S)$
unfolding no-cdcl_W-cp-iff-no-propagate-no-conflict
using assms **apply** (cases S, cases raw-conflicting S)
using do-propagate-step-no-step[of S]
by (auto dest!: do-cp-step-eq-no-prop-no-conf[simplified] do-conflict-step-no-step
split: option.splits)

lemma *cdcl_W-cp-cdcl_W-st*: $cdcl_W-cp\ S\ S' \implies cdcl_W^{**}\ S\ S'$
by (simp add: cdcl_W-cp-tranclp-cdcl_W tranclp-into-rtranclp)

lemma *cdcl_W-all-struct-inv-rough-state[simp]*: $cdcl_W-all-struct-inv\ (toS\ (rough-state-of\ S))$
using rough-state-of **by** auto

lemma [simp]: $cdcl_W-all-struct-inv\ (toS\ S) \implies rough-state-of\ (state-of\ S) = S$
by (simp add: state-of-inverse)

lemma *rough-state-of-state-of-do-cp-step[simp]*:
 $rough-state-of\ (state-of\ (do-cp-step\ (rough-state-of\ S))) = do-cp-step\ (rough-state-of\ S)$
proof –
have $cdcl_W-all-struct-inv\ (toS\ (do-cp-step\ (rough-state-of\ S)))$
apply (cases do-cp-step (rough-state-of S) = (rough-state-of S))
apply simp
using cp-step-is-cdcl_W-cp[of rough-state-of S] cdcl_W-all-struct-inv-rough-state[of S]
cdcl_W-cp-cdcl_W-st rtranclp-cdcl_W-all-struct-inv-inv **by** blast
then show ?thesis **by** auto
qed

Skip **fun** *do-skip-step* :: '*v* cdcl_W-state-inv-st \Rightarrow '*v* cdcl_W-state-inv-st **where**
do-skip-step (Propagated L C # Ls,N,U,k, Some D) =
(if $-L \notin set\ D \wedge D \neq []$

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 ≠ S ⇒ 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 ⇒ no-step skip (toS S)
by (induction S rule: do-skip-step.induct)
 (auto simp add: other split: if-split-asm elim: skipE)

lemma do-skip-step-raw-trail-is-None[iff]:

do-skip-step S = (a, b, c, d, None) ⟷ S = (a, b, c, d, None)
by (cases S rule: do-skip-step.cases) auto

Resolve fun maximum-level-code:: 'a literal list ⇒ ('a, 'a literal list) ann-lit list ⇒ 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 = get-maximum-level M (mset D)
by (induction D) (auto simp add: get-maximum-level-plus)

fun do-resolve-step :: 'v cdcl_W-state-inv-st ⇒ 'v cdcl_W-state-inv-st **where**

do-resolve-step (Propagated L C # Ls, N, U, k, Some D) =
 (if ¬L ∈ set D ∧ maximum-level-code (remove1 (¬L) D) (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) ⇒ do-resolve-step S ≠ S
 ⇒ 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 ∈ 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: if-split-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 ∈ set C **by** fastforce

then obtain C' **where** C: mset C = C' + {#L#}

by (metis add.commute in-multiset-in-set insert-DiffM)

obtain D' **where** D: mset D = D' + {#¬ L#}

using ⟨¬ L ∈ set D⟩ **by** (metis add.commute in-multiset-in-set insert-DiffM)

have D'L: D' + {#¬ L#} - {#¬ L#} = D' **by** (auto simp add: multiset-eq-iff)

have CL: mset C - {#L#} + {#L#} = mset C **using** ⟨L ∈ set C⟩ **by** (auto simp add: multiset-eq-iff)

have get-maximum-level (Propagated L (C' + {#L#}) # map convert M) D' = k

```

using  $M[simplified]$  unfolding maximum-level-code-eq-get-maximum-level  $C[symmetric]$   $CL$ 
by (metis  $D\ D'L$  convert.simps(1) get-maximum-level-map-convert list.simps(9))
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  $\langle cdcl_W\text{-all-struct-inv } (toS\ (Propagated\ L\ C\ \# M, N, U, k, Some\ D)) \rangle$ 
  unfolding cdcl_W-all-struct-inv-def distinct-cdcl_W-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  $\langle -L \in set\ D \rangle M$  by (auto simp:ac-simps mset-map)
ultimately show ?case
  by simp
qed auto

```

```

lemma do-resolve-step-no:
  do-resolve-step  $S = S \implies no\text{-step } resolve\ (toS\ S)$ 
apply (cases  $S$ ; cases hd (raw-trail  $S$ ); cases raw-trail  $S$ ; cases raw-conflicting  $S$ )
by (auto
  elim!: resolveE split: if-split-asm
  dest!: union-single-eq-member
  simp del: in-multiset-in-set get-maximum-level-map-convert
  simp: get-maximum-level-map-convert[symmetric])

```

```

lemma rough-state-of-state-of-resolve[simp]:
  cdcl_W-all-struct-inv (toS  $S$ )  $\implies rough\text{-state-of } (state\text{-of } (do\text{-resolve-step } S)) = do\text{-resolve-step } S$ 
apply (rule state-of-inverse)
apply (cases do-resolve-step  $S = S$ )
apply simp
by (blast dest: other resolve bj do-resolve-step cdcl_W-all-struct-inv-inv)

```

```

lemma do-resolve-step-raw-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 lemma get-all-ann-decomposition-map-convert:
  (get-all-ann-decomposition (map convert  $M$ )) =
    map ( $\lambda(a, b). (map\ convert\ a, map\ convert\ b)$ ) (get-all-ann-decomposition  $M$ )
apply (induction  $M$  rule: ann-lit-list-induct)
apply simp
by (rename-tac  $L\ xs$ , case-tac get-all-ann-decomposition  $xs$ ; auto) $+$ 

```

lemma *do-backtrack-step*:

assumes

db: *do-backtrack-step* $S \neq S$ **and**

inv: *cdcl_W-all-struct-inv* (*toS* S)

shows *backtrack* (*toS* S) (*toS* (*do-backtrack-step* S))

proof (*cases* S , *cases raw-conflicting* S , *goal-cases*)

case ($1\ M\ N\ U\ k\ E$)

then show *?case* **using** *db* **by** *auto*

next

case ($2\ M\ N\ U\ k\ E\ C$) **note** $S = \text{this}(1)$ **and** $\text{confl} = \text{this}(2)$

have $E: E = \text{Some } C$ **using** $S\ \text{confl}$ **by** *auto*

obtain $L\ j$ **where** *fd*: *find-level-decomp* $M\ C\ []\ k = \text{Some } (L, j)$

using *db unfolding* $S\ E$ **by** (*cases* C) (*auto split: if-split-asm option.splits list.splits ann-lit.splits*)

have

$L \in \text{set } C$ **and**

j: *get-maximum-level* $M\ (\text{mset } (\text{remove1 } L\ C)) = j$ **and**

levL: *get-level* $M\ L = k$

using *find-level-decomp-some*[*OF fd*] **by** *auto*

obtain C' **where** $C: \text{mset } C = \text{mset } C' + \{\#L\#$

using $\langle L \in \text{set } C \rangle$ **by** (*metis add commute ex-mset in-multiset-in-set insert-DiffM*)

obtain $M2$ **where** $M2: \text{bt-cut } j\ M = \text{Some } M2$

using *db fd unfolding* $S\ E$ **by** (*auto split: option.splits*)

have *no-dup* M **and** *k*: $k = \text{count-decided } (\text{filter is-decided } M)$

using *inv unfolding* *cdcl_W-all-struct-inv-def* *cdcl_W-M-level-inv-def* S **by** (*auto simp: comp-def*)

then obtain $M1\ K\ c$ **where**

$M1: M2 = \text{Decided } K \# M1$ **and** *lev-K*: *get-level* $M\ K = j + 1$ **and**

$c: M = c \ @\ M2$

using *bt-cut-some-decomp*[*OF - M2*] **by** (*cases* $M2$) *auto*

have $j \leq k$ **unfolding** $c\ j[\text{symmetric}]$ k

by (*metis (mono-tags, lifting) count-decided-ge-get-maximum-level filter-cong filter-filter*)

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 ann-lit.splits

dest!: *find-level-decomp-some*)[1]

have *get-maximum-level* $M\ (\text{mset } C) \geq k$

using $\langle L \in \text{set } C \rangle$ *levL* *get-maximum-level-ge-get-level* **by** (*metis set-mset-mset*)

moreover have *get-maximum-level* $M\ (\text{mset } C) \leq k$

using *get-maximum-level-exists-lit-of-max-level*[*of mset C M*] *inv*

cdcl_W-M-level-inv-get-level-le-backtrack-lvl[*of toS S*]

unfolding $C\ \text{cdcl}_W\text{-all-struct-inv-def } S$ **by** (*auto dest: sym*[*of get-level - -*])

ultimately have *get-maximum-level* $M\ (\text{mset } C) = k$ **by** *auto*

obtain $M2'$ **where** $M2': (M2, M2') \in \text{set } (\text{get-all-ann-decomposition } M)$

using *bt-cut-in-get-all-ann-decomposition*[*OF (no-dup M) M2*] **by** *metis*

have *decomp*:

(*Decided* $K \# (\text{map convert } M1)$,

(*map convert* $M2'$)) \in

set (*get-all-ann-decomposition* (*map convert* M))

using *imageI*[*of - - $\lambda(a, b). (\text{map convert } a, \text{map convert } b), \text{OF } M2'$*] j

unfolding $S\ E\ M1$ **by** (*simp add: get-all-ann-decomposition-map-convert*)

show *?case*

apply (*rule backtrack-rule*)

using $M2\ \text{fd}\ \text{confl}\ \langle L \in \text{set } C \rangle\ j\ \text{decomp}\ \text{levL}\ \langle \text{get-maximum-level } M\ (\text{mset } C) = k \rangle$

unfolding $S\ E\ M1$ **apply** (*auto simp: mset-map*)[6]


```

    using M2' M2 fd j lev-K unfolding S E M1 CDCL-W-Implementation.state-eq-def
    by (auto simp: comp-def ac-simps)[2]
qed

lemma map-eq-list-length:
  map f L = L'  $\implies$  length L = length L'
  by auto

lemma map-mmset-of-mlit-eq-cons:
  assumes map convert M = a @ c
  obtains a' c' where
    M = a' @ c' and
    a = map convert a' and
    c = map convert c'
  using that[of take (length a) M drop (length a) M]
  assms by (metis append-eq-conv-conj append-take-drop-id drop-map take-map)

lemma Decided-convert-iff:
  Decided K = convert za  $\longleftrightarrow$  za = Decided K
  by (cases za) auto

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 raw-conflicting S, goal-cases)
  case 1
  then show ?case using db by (auto split: option.splits elim: backtrackE)
next
  case (2 M N U k E C) note bt = this(1) and S = this(2) and confl = this(3)
  obtain K j M1 M2 L D where
    CE: raw-conflicting S = Some D and
    LD: L  $\in$  # mset D and
    decomp: (Decided K # M1, M2)  $\in$  set (get-all-ann-decomposition (raw-trail S)) and
    levL: get-level (raw-trail S) L = raw-backtrack-lvl S and
    k: get-level (raw-trail S) L = get-maximum-level (raw-trail S) (mset D) and
    j: get-maximum-level (raw-trail S) (remove1-mset L (mset D))  $\equiv$  j and
    lev-K: get-level (raw-trail S) K = Suc j
  using bt apply clarsimp
  apply (elim backtrackE)
  apply (cases S)
  by (auto simp add: get-all-ann-decomposition-map-convert reduce-trail-to
    Decided-convert-iff)
  obtain c where c: raw-trail S = c @ M2 @ Decided K # M1
  using decomp by blast
  have k = count-decided (raw-trail S) and n-d: no-dup M
  using inv S unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def
  by (auto simp: comp-def)
  then have k > j
  using j count-decided-ge-get-maximum-level[of raw-trail S remove1-mset L (mset D)]
  count-decided-ge-get-level[of K raw-trail S]
  unfolding k lev-K
  unfolding c by (auto simp: get-all-ann-decomposition-map-convert simp del: count-decided-ge-get-level)
  have [simp]: L  $\in$  set D
  using LD by auto

```

```

have CD: C = D
  using CE confl by auto
obtain D' where
  E: E = Some D and
  DD': mset D = {#L#} + mset D'
  using that[of remove1 L D]
  using S CE confl LD by (auto simp add: insert-DiffM)
have find-level-decomp M D [] k ≠ None
  apply rule
  apply (drule find-level-decomp-none[of - - - L D'])
  using DD' ⟨k > j⟩ mset-eq-setD S levL unfolding k[symmetric] j[symmetric]
  by (auto simp: ac-simps)
then obtain L' j' where fd-some: find-level-decomp M D [] k = Some (L', j')
  by (cases find-level-decomp M D [] k) auto
have L': L' = L
  proof (rule ccontr)
    assume ¬ ?thesis
    then have L' ∈ # mset (remove1 L D)
      by (metis fd-some find-level-decomp-some in-set-remove1 set-mset-mset)
    then have get-level M L' ≤ get-maximum-level M (mset (remove1 L D))
      using get-maximum-level-ge-get-level by blast
    then show False using ⟨k > j⟩ j find-level-decomp-some[OF fd-some] S DD' by auto
  qed
then have j': j' = j using find-level-decomp-some[OF fd-some] j S DD' by auto

obtain c' M1' where cM: M = c' @ Decided K # M1'
  apply (rule map-mmset-of-mlit-eq-cons[of M map convert (c @ M2)
    map convert (Decided K # M1)])
  using c S apply simp
  apply (rule map-mmset-of-mlit-eq-cons[of - map convert [Decided K] map convert M1])
  apply auto[]
  apply (rename-tac a b' aa b, case-tac aa)
  apply auto[]
  apply (rename-tac a b' aa b, case-tac aa)
  by auto
have btc-none: bt-cut j M ≠ None
  apply (rule bt-cut-not-none[of M ])
  using n-d cM S lev-K S apply blast+
  using lev-K S by auto
show ?case using db n-d unfolding S E
  by (auto split: option.splits list.splits ann-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)
  consider
    (step) backtrack (toS S) (toS (do-backtrack-step S)) |
    (0) do-backtrack-step S = S
  using do-backtrack-step inv by blast
then show do-backtrack-step S ∈ {S. cdclW-all-struct-inv (toS S)}
  proof cases
    case 0

```

```

    thus ?thesis using inv by simp
next
  case step
  then show ?thesis
    using inv
    by (auto dest!: cdclW.other cdclW-o.bj cdclW-bj.backtrack intro: cdclW-all-struct-inv-inv)
qed
qed

```

Decide fun *do-decide-step* where
do-decide-step (*M*, *N*, *U*, *k*, *None*) =
 (case *find-first-unused-var* *N* (*lits-of-l* *M*) of
None \Rightarrow (*M*, *N*, *U*, *k*, *None*)
 | *Some* *L* \Rightarrow (*Decided* *L* # *M*, *N*, *U*, *k*+1, *None*)) |
do-decide-step *S* = *S*

lemma *do-decide-step*:
do-decide-step *S* \neq *S* \implies *decide* (*toS* *S*) (*toS* (*do-decide-step* *S*))
apply (*cases* *S*, *cases raw-conflicting* *S*)
defer
apply (*auto split: option.splits simp add: decide.simps*
dest: find-first-unused-var-undefined find-first-unused-var-Some
intro: atms-of-atms-of-ms-mono)[1]

proof –
fix *a* :: ('a, 'a literal list) ann-lit list **and**
b :: 'a literal list list **and** *c* :: 'a literal list list **and**
d :: nat **and** *e* :: 'a literal list option
{
fix *a* :: ('a, 'a literal list) ann-lit list **and**
b :: 'a literal list list **and** *c* :: 'a literal list list **and**
d :: nat **and** *x2* :: 'a literal **and** *m* :: 'a literal list
assume *a1*: *m* \in *set* *b*
assume *x2* \in *set* *m*
then have *f2*: *atm-of* *x2* \in *atms-of* (*mset* *m*)
 by *simp*
have $\bigwedge f. (f\ m :: 'a\ literal\ multiset) \in f\ 'set\ b$
 using *a1* by *blast*
then have $\bigwedge f. (atms-of\ (f\ m) :: 'a\ set) \subseteq atms-of-ms\ (f\ 'set\ b)$
 using *atms-of-atms-of-ms-mono* by *blast*
then have $\bigwedge n\ f. (n :: 'a) \in atms-of-ms\ (f\ 'set\ b) \vee n \notin atms-of\ (f\ m)$
 by (*meson contra-subsetD*)
then have *atm-of* *x2* \in *atms-of-ms* (*mset* ' *set* *b*)
 using *f2* by *blast*
} **note** *H* = *this*
{
fix *m* :: 'a literal list **and** *x2*
have *m* \in *set* *b* \implies *x2* \in *set* *m* \implies *x2* \notin *lits-of-l* *a* \implies \neg *x2* \notin *lits-of-l* *a* \implies
 $\exists aa \in set\ b. \neg atm-of\ 'set\ aa \subseteq atm-of\ 'lits-of-l\ a$
 by (*meson atm-of-in-atm-of-set-in-uminus contra-subsetD rev-image-eqI*)
} **note** *H'* = *this*

assume *do-decide-step* *S* \neq *S* **and**
S = (*a*, *b*, *c*, *d*, *e*) **and**
raw-conflicting *S* = *None*
then show *decide* (*toS* *S*) (*toS* (*do-decide-step* *S*))
 using *H* *H'* by (*auto split: option.splits simp: decide.simps defined-lit-map lits-of-def*)

image-image atm-of-eq-atm-of dest!: find-first-unused-var-Some)
qed

lemma *do-decide-step-no*:

do-decide-step S = S \implies no-step decide (toS S)

apply (*cases S, cases raw-conflicting S*)

apply (*auto simp: atms-of-ms-mset-unfold Decided-Propagated-in-iff-in-lits-of-l lits-of-def*
dest!: atm-of-in-atm-of-set-in-uminus
elim!: decideE
split: option.splits)
using *atm-of-eq-atm-of* **by** *blast*+

lemma *rough-state-of-state-of-do-decide-step[simp]*:

cdcl_W-all-struct-inv (toS S) \implies rough-state-of (state-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-all-struct-inv (toS S) \implies rough-state-of (state-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*)
 +

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-of (if cdcl_W-all-struct-inv (toS (fst xs, snd xs)) then xs
else ([], [], [], 0, None))

lemma [*code abstype*]:

Con (rough-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-of (do-cp-step (rough-state-of S))

typedef '*v* *cdcl_W-state-inv-from-init-state* =

{*S*:: '*v* *cdcl_W-state-inv-st. cdcl_W-all-struct-inv (toS S)*

\wedge *cdcl_W-stgy** (S0-cdcl_W (raw-init-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-all-struct-inv (toS S)*

\wedge *cdcl_W-stgy** (S0-cdcl_W (raw-init-clss (toS S))) (toS S)*}

by (*auto simp add: cdcl_W-all-struct-inv-def*)

qed

instantiation *cdcl_W-state-inv-from-init-state* :: (*type*) *equal*

begin

definition *equal-cdcl_W-state-inv-from-init-state* :: 'v cdcl_W-state-inv-from-init-state \Rightarrow 'v cdcl_W-state-inv-from-init-state \Rightarrow bool **where**
equal-cdcl_W-state-inv-from-init-state *S S'* \longleftrightarrow
 (rough-state-from-init-state-of *S* = 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 = state-from-init-state-of (if cdcl_W-all-struct-inv (toS (fst *S*, snd *S*))
 \wedge cdcl_W-stgy* (S0-cdcl_W (raw-init-clss (toS *S*))) (toS *S*) then *S* else ([], [], [], 0, 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*:: 'v cdcl_W-state-inv-from-init-state \Rightarrow 'v cdcl_W-state-inv **where**
id-of-I-to S = state-of (rough-state-from-init-state-of *S*)

lemma [code abstract]:

rough-state-of (*id-of-I-to S*) = rough-state-from-init-state-of *S*
unfolding *id-of-I-to-def* **using** rough-state-from-init-state-of[of *S*] **by** *auto*

Conflict and Propagate function *do-full1-cp-step* :: 'v cdcl_W-state-inv \Rightarrow 'v cdcl_W-state-inv **where**

do-full1-cp-step S =
 (let *S'* = *do-cp-step'* *S* in
 if *S* = *S'* then *S* else *do-full1-cp-step S'*)

by *auto*

termination

proof (relation {(*T'*, *T*). (rough-state-of *T'*, rough-state-of *T*) \in {(*S'*, *S*).
 (toS *S'*, toS *S*) \in {(*S'*, *S*). cdcl_W-all-struct-inv *S* \wedge cdcl_W-cp *S S'*}}}, goal-cases)
case 1
show ?*case*
using wf-if-measure-f[OF wf-if-measure-f[OF cdcl_W-cp-wf-all-inv, of toS], of rough-state-of] .

next

case (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 $\lambda S. do-cp-step(rough-state-of (do-full1-cp-step S))$
 = (rough-state-of (*do-full1-cp-step S*))])
 (*metis* (full-types) *do-full1-cp-step.elims* rough-state-of-state-of-do-cp-step *do-cp-step'-def*)

lemma *in-clauses-rough-state-of-is-distinct*:

c \in set (raw-init-clss (rough-state-of *S*) @ raw-learned-clss (rough-state-of *S*)) \implies distinct *c*
apply (*cases* rough-state-of *S*)
using rough-state-of[of *S*] **by** (*auto simp add: distinct-mset-set-distinct cdcl_W-all-struct-inv-def*)

distinct-cdcl_W-state-def)

lemma *do-full1-cp-step-full*:

full cdcl_W-cp (toS (rough-state-of S))
 (toS (rough-state-of (do-full1-cp-step S)))

unfolding *full-def*

proof (rule *conjI*, induction S rule: *do-full1-cp-step.induct*)

case (1 S)

then have *f1*:

*cdcl_W-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))))))
 \vee state-of (do-cp-step (rough-state-of S)) = S

using *rough-state-of-state-of-do-cp-step* **unfolding** *do-cp-step'-def* **by** *fastforce*

have *f2*: $\wedge c$. (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*: \neg *cdcl_W-cp* (toS (rough-state-of S)) (toS (do-cp-step (rough-state-of S)))
 \vee state-of (do-cp-step (rough-state-of S)) = S

\vee *cdcl_W-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 \neq S

then have *do-cp-step* (rough-state-of S) = rough-state-of S
 \longrightarrow *cdcl_W-cp*** (toS (rough-state-of S)) (toS (rough-state-of (do-full1-cp-step S)))

\vee *do-cp-step* (rough-state-of S) \neq rough-state-of S
 \wedge state-of (do-cp-step (rough-state-of S)) \neq S

using *f2 f1* **by** (metis (no-types))

then have *do-cp-step* (rough-state-of S) \neq rough-state-of S
 \wedge state-of (do-cp-step (rough-state-of S)) \neq S

\vee *cdcl_W-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 *cdcl_W-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-cdcl_W-cp* *tranclp-into-rtranclp*) }

then show ?case

by *fastforce*

next

show *no-step cdcl_W-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*]:

rough-state-of (do-cp-step' S) = *do-cp-step* (rough-state-of S)

unfolding *do-cp-step'-def* **by** *auto*

The other rules **fun** *do-other-step* **where**

do-other-step S =

(let T = *do-skip-step* S in

if T \neq S

then T

else

(let U = *do-resolve-step* T in

if U \neq T

then U else

(let V = *do-backtrack-step* U in

if $V \neq U$ then V else do-decide-step V)))

lemma *do-other-step:*

assumes *inv: cdcl_W-all-struct-inv (toS S) and*
st: do-other-step S \neq S
shows *cdcl_W-o (toS S) (toS (do-other-step S))*
using *st inv by (auto split: if-split-asm*
simp add: Let-def
dest!: do-skip-step do-resolve-step do-backtrack-step do-decide-step
dest!: cdcl_W-o.intros cdcl_W-bj.intros)

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: if-split-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*: $\text{do-full1-cp-step } S \neq S \implies$
 $\text{toS } (\text{rough-state-of } S) \neq \text{toS } (\text{rough-state-of } (\text{do-full1-cp-step } S))$
proof –
assume *a1*: $\text{do-full1-cp-step } S \neq S$
then have $S \neq \text{do-cp-step}' S$
by *fastforce*
then show *?thesis*
by (*metis* (*no-types*) *cp-step-is-cdcl_W-cp do-cp-step'-def do-cp-step-eq-no-step*
do-full1-cp-step-fix-point-of-do-full1-cp-step in-clauses-rough-state-of-is-distinct
rough-state-of-inverse)

qed

do-full1-cp-step should not be unfolded anymore:

declare *do-full1-cp-step.simps*[*simp del*]

Correction of the transformation **lemma** *do-cdcl_W-stgy-step*:

assumes *do-cdcl_W-stgy-step* $S \neq S$
shows *cdcl_W-stgy* ($\text{toS } (\text{rough-state-of } S)$) ($\text{toS } (\text{rough-state-of } (\text{do-cdcl_W-stgy-step } S))$)
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* ($\text{toS } (\text{rough-state-of } S)$) ($\text{toS } (\text{rough-state-of } (\text{do-other-step}' S))$)
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* ($\text{toS } (\text{rough-state-of } S)$) **and**
nc: *no-step conflict* ($\text{toS } (\text{rough-state-of } S)$)
apply (*metis True do-cp-step-eq-no-prop-no-conf*
do-full1-cp-step-fix-point-of-do-full1-cp-step do-propagate-step-no-step
in-clauses-rough-state-of-is-distinct)
by (*metis True do-conflict-step-no-step do-cp-step-eq-no-prop-no-conf*
do-full1-cp-step-fix-point-of-do-full1-cp-step)
then have *no-step cdcl_W-cp* ($\text{toS } (\text{rough-state-of } S)$)
by (*simp add: cdcl_W-cp.simps*)
moreover have *full cdcl_W-cp* ($\text{toS } (\text{rough-state-of } (\text{do-other-step}' S))$)
($\text{toS } (\text{rough-state-of } (\text{do-full1-cp-step } (\text{do-other-step}' S)))$)
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-raw-trail-toS*[*simp*]:
 $\text{length } (\text{raw-trail } (\text{toS } S)) = \text{length } (\text{raw-trail } S)$
by (*cases S auto*)

lemma *raw-conflicting-noTrue-iff-toS*[*simp*]:
 $\text{raw-conflicting } (\text{toS } S) \neq \text{None} \longleftrightarrow \text{raw-conflicting } S \neq \text{None}$
by (*cases S auto*)

lemma *raw-trail-toS-neq-imp-raw-trail-neq*:
 $\text{raw-trail } (toS \ S) \neq \text{raw-trail } (toS \ S') \implies \text{raw-trail } S \neq \text{raw-trail } S'$
by (cases S , cases S') *auto*

lemma *do-skip-step-raw-trail-changed-or-conflict*:
assumes d : $\text{do-other-step } S \neq S$
and inv : $\text{cdcl}_W\text{-all-struct-inv } (toS \ S)$
shows $\text{raw-trail } S \neq \text{raw-trail } (\text{do-other-step } S)$

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 $\text{cdcl}_W\text{-M-level-inv } (toS \ S)$
using inv **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ **by** *auto*
have $\text{cdcl}_W\text{-o } (toS \ S) \ (toS \ (\text{do-other-step } S))$ **using** $\text{do-other-step}[OF \ inv \ d]$.
then show *?thesis*
using $\langle \text{cdcl}_W\text{-M-level-inv } (toS \ S) \rangle$
proof (*induction toS (do-other-step S) rule: cdcl_W-o-induct*)
case *decide*
then show *?thesis*
by (*auto simp add: raw-trail-toS-neq-imp-raw-trail-neq*)[]
next
case (*skip*)
then show *?case*
by (cases S ; cases $\text{do-other-step } S$) *force*
next
case (*resolve*)
then show *?case*
by (cases S , cases $\text{do-other-step } S$) *force*
next
case (*backtrack L D K i M1 M2*) **note** $LD = \text{this}(2)$ **and** $\text{decomp} = \text{this}(3)$ **and** $\text{confl-}S = \text{this}(1)$
and $i = \text{this}(6)$ **and** $U = \text{this}(8)$

have
 bt : $\text{raw-backtrack-lvl } (toS \ S) = \text{count-decided } (\text{raw-trail } (toS \ S))$ **and**
 $\text{raw-trail } (toS \ S) \models_{as} CNot \ D$ **and**
 $cons$: $\text{consistent-interp } (\text{lits-of-l } (\text{raw-trail } (toS \ S)))$
using $inv \ \text{confl-}S$ **unfolding** $\text{cdcl}_W\text{-all-struct-inv-def}$ $\text{cdcl}_W\text{-M-level-inv-def}$
 $\text{cdcl}_W\text{-conflicting-def}$ **by** *simp-all*
then have $-L \in \text{lits-of-l } (\text{raw-trail } (toS \ S))$
using $LD \ \text{true-annots-true-cls-def-iff-negation-in-model}$ **by** *blast*
then have $-L \in \text{lits-of-l } (\text{raw-trail } S)$
by (cases S) (*auto simp: lits-of-def*)
moreover have $\text{consistent-interp } (\text{lits-of-l } (\text{raw-trail } S))$
using $cons$ **by** (cases S) (*auto simp: lits-of-def image-image*)
ultimately have $L \notin \text{lits-of-l } (\text{raw-trail } S)$
using $\text{consistent-interp-def}$ **by** *blast*

moreover
have $L \in \text{lits-of-l } (\text{raw-trail } (toS \ (\text{do-other-step } S)))$
using U **by** *auto*
then have $L \in \text{lits-of-l } (\text{raw-trail } (\text{do-other-step } S))$
by (cases $\text{do-other-step } S$) (*auto simp: lits-of-def*)
ultimately show *?thesis*
by *metis*

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-raw-trail-increase*:

$\exists c. \text{raw-trail } (\text{do-cp-step } S) = c @ \text{raw-trail } S \wedge (\forall m \in \text{set } c. \neg \text{is-decided } m)$
by (*cases S, cases raw-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-raw-trail-increase*:

$\exists c. \text{raw-trail } (\text{rough-state-of } (\text{do-full1-cp-step } S)) = c @ \text{raw-trail } (\text{rough-state-of } S)$
 $\wedge (\forall m \in \text{set } c. \neg \text{is-decided } m)$
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-raw-trail-increase do-full1-cp-step.simps*
rough-state-of-state-of-do-cp-step set-append)

lemma *do-cp-step-raw-conflicting*:

raw-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-raw-conflicting*:

raw-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-raw-conflicting)

lemma *do-decide-step-not-raw-conflicting-one-more-decide*:

assumes
raw-conflicting S = None and
do-decide-step S \neq S
shows *Suc (length (filter is-decided (raw-trail S)))*
 $= \text{length } (\text{filter is-decided } (\text{raw-trail } (\text{do-decide-step } S)))$
using *assms unfolding do-other-step'-def*
by (*cases S (auto simp: Let-def split: if-split-asm option.splits*
dest!: find-first-unused-var-Some-not-all-incl))

lemma *do-decide-step-not-raw-conflicting-one-more-decide-bt*:

assumes *raw-conflicting S \neq None and*
do-decide-step S \neq S
shows *length (filter is-decided (raw-trail S)) < length (filter is-decided (raw-trail (do-decide-step S)))*
using *assms unfolding do-other-step'-def* **by** (*cases S, cases raw-conflicting S*)
(auto simp add: Let-def split: if-split-asm option.splits)

lemma *count-decided-raw-trail-toS*:

count-decided (raw-trail (toS S)) = count-decided (raw-trail S)
by (*cases S (auto simp: comp-def)*)

lemma *do-other-step-not-raw-conflicting-one-more-decide-bt*:

assumes
raw-conflicting (rough-state-of S) \neq None and
raw-conflicting (rough-state-of (do-other-step' S)) = None and
do-other-step' S \neq S

```

shows count-decided (raw-trail (rough-state-of S))
  > count-decided (raw-trail (rough-state-of (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, Some E)
  using assms(1) S inv by (cases y, cases raw-conflicting y) auto
  have M: rough-state-of (state-of (M, N, U, k, Some E)) = (M, N, U, k, Some E)
  using inv y by (auto simp add: state-of-inverse)
  have bt: do-other-step' S = state-of (do-backtrack-step (rough-state-of S))
  proof (cases rough-state-of S rule: do-decide-step.cases)
  case 1
  then show ?thesis
    using assms(1,2) by auto[]
  next
  case (2 v vb vd vf vh)
  have f3:  $\bigwedge c. (if\ do-skip-step\ (rough-state-of\ c) \neq rough-state-of\ c$ 
    then do-skip-step (rough-state-of c)
    else if do-resolve-step (do-skip-step (rough-state-of c))  $\neq$  do-skip-step (rough-state-of c)
      then do-resolve-step (do-skip-step (rough-state-of c))
      else if do-backtrack-step (do-resolve-step (do-skip-step (rough-state-of c)))
         $\neq$  do-resolve-step (do-skip-step (rough-state-of c))
        then do-backtrack-step (do-resolve-step (do-skip-step (rough-state-of c)))
        else do-decide-step (do-backtrack-step (do-resolve-step
          (do-skip-step (rough-state-of c))))))
    = rough-state-of (do-other-step' c)
  by (simp add: rough-state-of-do-other-step')
  have (raw-trail (rough-state-of (do-other-step' S)), raw-init-clss (rough-state-of (do-other-step' S)),
    raw-learned-clss (rough-state-of (do-other-step' S)),
    raw-backtrack-lvl (rough-state-of (do-other-step' S)), None)
    = rough-state-of (do-other-step' S)
  using assms(2) by (metis (no-types) state-conv)
  then show ?thesis
    using f3 2 by (metis (no-types) do-decide-step.simps(2) do-resolve-step-raw-trail-is-None
      do-skip-step-raw-trail-is-None rough-state-of-inverse)
  qed
have
  bt: raw-backtrack-lvl (toS y) = count-decided (raw-trail (toS y))
  using inv unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def
    cdclW-conflicting-def by simp-all
  have confl-y: raw-conflicting (toS (rough-state-of (do-other-step' (state-of y)))) = None
  using assms(2) y S raw-conflicting-noTrue-iff-toS by blast
  have backtrack (toS (rough-state-of S))
    (toS (rough-state-of (do-other-step' (state-of y))))  $\vee$ 
    resolve (toS (rough-state-of S))
    (toS (rough-state-of (do-other-step' (state-of y))))  $\vee$ 
    skip (toS (rough-state-of S))
    (toS (rough-state-of (do-other-step' (state-of y))))
  proof -
  have f1: (M, N, U, k, Some E) = rough-state-of S
    by (simp add: M S y)
  then have f2: do-other-step (M, N, U, k, Some E)  $\neq$  (M, N, U, k, Some E)
    by (metis assms(3) rough-state-of-do-other-step' rough-state-of-inject)
  have cdclW-all-struct-inv (toS (M, N, U, k, Some E))
    using f1 by simp
  then have cdclW-o (toS (M, N, U, k, Some E)) (toS (do-other-step (M, N, U, k, Some E)))
    using f2 do-other-step by blast

```

```

then have f3: cdclW-o (toS (rough-state-of S))
  (toS (rough-state-of (do-other-step' (state-of (M, N, U, k, Some E))))))
using f1 by (simp add: rough-state-of-do-other-step')
have ¬ decide (toS (rough-state-of S))
  (toS (rough-state-of (do-other-step' (state-of (M, N, U, k, Some E))))))
using f1 by (metis (no-types) do-decide-step.simps(2) do-decide-step-no)
then show ?thesis
  using f3 cdclW-o-rule-cases y by blast
qed
then have bt: backtrack (toS (rough-state-of S))
  (toS (rough-state-of (do-other-step' (state-of y))))
using confl-y by (cases rough-state-of S) (auto elim!: resolveE skipE)
moreover
have no-dup (raw-trail (rough-state-of S))
  using rough-state-of[of S] unfolding cdclW-all-struct-inv-def cdclW-M-level-inv-def
  by (cases S) (auto simp: comp-def)
have cdclW-M-level-inv (toS (rough-state-of S)) and
  cdclW-M-level-inv (toS (rough-state-of (do-other-step' (state-of y))))
  using inv apply (simp add: cdclW-all-struct-inv-def S)
using cdclW-all-struct-inv-def cdclW-all-struct-inv-rough-state by blast
then show ?case
  using backtrack-lvl-backtrack-decrease[OF - bt]
  using S unfolding cdclW-M-level-inv-def
  by (simp add: comp-def count-decided-raw-trail-toS)
qed

lemma do-other-step-not-raw-conflicting-one-more-decide:
  assumes raw-conflicting (rough-state-of S) = None and
  do-other-step' S ≠ S
shows 1 + length (filter is-decided (raw-trail (rough-state-of S)))
  = length (filter is-decided (raw-trail (rough-state-of (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 where y: y = (M, N, U, k, None) using assms(1) S inv by (cases y) auto
have M: rough-state-of (state-of (M, N, U, k, None)) = (M, N, U, k, None)
  using inv y by (auto simp add: state-of-inverse)
have state-of (do-decide-step (M, N, U, k, None)) ≠ state-of (M, N, U, k, None)
  using assms(2) unfolding do-other-step'-def y inv S by (auto simp add: M)
then have f4: do-skip-step (rough-state-of S) = rough-state-of S
  unfolding S M y by (metis (full-types) do-skip-step.simps(4))
have f5: do-resolve-step (rough-state-of S) = rough-state-of S
  unfolding S M y by (metis (no-types) do-resolve-step.simps(4))
have f6: do-backtrack-step (rough-state-of S) = rough-state-of S
  unfolding S M y by (metis (no-types) do-backtrack-step.simps(2))
have do-other-step (rough-state-of S) ≠ rough-state-of S
  using assms(2) unfolding S M y do-other-step'-def by (metis (no-types))
then show ?case
  using f6 f5 f4 by (simp add: assms(1) do-decide-step-not-raw-conflicting-one-more-decide
    do-other-step'-def)
qed

lemma rough-state-of-state-of-do-skip-step-rough-state-of[simp]:
  rough-state-of (state-of (do-skip-step (rough-state-of S))) = 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 raw-conflicting-do-resolve-step-iff[iff]:

```

$\text{raw-conflicting } (\text{do-resolve-step } S) = \text{None} \longleftrightarrow \text{raw-conflicting } S = \text{None}$
by (cases S rule: $\text{do-resolve-step.cases}$)
(auto simp add: Let-def split: option.splits)

lemma $\text{raw-conflicting-do-skip-step-iff}[iff]$:
 $\text{raw-conflicting } (\text{do-skip-step } S) = \text{None} \longleftrightarrow \text{raw-conflicting } S = \text{None}$
by (cases S rule: $\text{do-skip-step.cases}$)
(auto simp add: Let-def split: option.splits)

lemma $\text{raw-conflicting-do-decide-step-iff}[iff]$:
 $\text{raw-conflicting } (\text{do-decide-step } S) = \text{None} \longleftrightarrow \text{raw-conflicting } S = \text{None}$
by (cases S rule: $\text{do-decide-step.cases}$)
(auto simp add: Let-def split: option.splits)

lemma $\text{raw-conflicting-do-backtrack-step-imp}[simp]$:
 $\text{do-backtrack-step } S \neq S \implies \text{raw-conflicting } (\text{do-backtrack-step } S) = \text{None}$
by (cases S rule: $\text{do-backtrack-step.cases}$)
(auto simp add: Let-def split: list.splits option.splits ann-lit.splits)

lemma $\text{do-skip-step-eq-iff-raw-trail-eq}$:
 $\text{do-skip-step } S = S \longleftrightarrow \text{raw-trail } (\text{do-skip-step } S) = \text{raw-trail } S$
by (cases S rule: $\text{do-skip-step.cases}$) auto

lemma $\text{do-decide-step-eq-iff-raw-trail-eq}$:
 $\text{do-decide-step } S = S \longleftrightarrow \text{raw-trail } (\text{do-decide-step } S) = \text{raw-trail } S$
by (cases S rule: $\text{do-decide-step.cases}$) (auto split: option.split)

lemma $\text{do-backtrack-step-eq-iff-raw-trail-eq}$:
assumes no-dup (raw-trail S)
shows $\text{do-backtrack-step } S = S \longleftrightarrow \text{raw-trail } (\text{do-backtrack-step } S) = \text{raw-trail } S$
using assms **apply** (cases S rule: $\text{do-backtrack-step.cases}$)
by (auto split: option.split list.splits ann-lit.splits
simp: comp-def
dest!: bt-cut-in-get-all-ann-decomposition)

lemma $\text{do-resolve-step-eq-iff-raw-trail-eq}$:
 $\text{do-resolve-step } S = S \longleftrightarrow \text{raw-trail } (\text{do-resolve-step } S) = \text{raw-trail } S$
by (cases S rule: $\text{do-resolve-step.cases}$) auto

lemma $\text{do-other-step-eq-iff-raw-trail-eq}$:
assumes no-dup (raw-trail S)
shows $\text{raw-trail } (\text{do-other-step } S) = \text{raw-trail } S \longleftrightarrow \text{do-other-step } S = S$
using assms
by (auto simp add: Let-def do-skip-step-eq-iff-raw-trail-eq[symmetric]
do-decide-step-eq-iff-raw-trail-eq[symmetric] do-backtrack-step-eq-iff-raw-trail-eq[symmetric]
do-resolve-step-eq-iff-raw-trail-eq[symmetric])

lemma $\text{do-full1-cp-step-do-other-step'-normal-form}[dest!]$:
assumes H : $\text{do-full1-cp-step } (\text{do-other-step}' S) = S$
shows $\text{do-other-step}' S = S \wedge \text{do-full1-cp-step } S = S$
proof –
let $?T = \text{do-other-step}' S$
{ **assume** conf! : $\text{raw-conflicting } (\text{rough-state-of } ?T) \neq \text{None}$
then have tr : $\text{raw-trail } (\text{rough-state-of } (\text{do-full1-cp-step } ?T)) = \text{raw-trail } (\text{rough-state-of } ?T)$
using $\text{do-full1-cp-step-raw-conflicting}[of ?T]$ **by** auto

```

have raw-trail (rough-state-of (do-full1-cp-step (do-other-step' S))) = raw-trail (rough-state-of S)
  using arg-cong[OF H, of  $\lambda S. \text{raw-trail (rough-state-of S)}$ ] .
then have raw-trail (rough-state-of (do-other-step' S)) = raw-trail (rough-state-of S)
  by (auto simp add: do-full1-cp-step-raw-conflicting confl)
then have do-other-step' S = S
  using assms confl
  by (simp add: do-other-step-eq-iff-raw-trail-eq do-other-step'-def
    do-full1-cp-step-raw-conflicting
    del: do-other-step.simps)
}
moreover {
  assume eq[simp]: do-other-step' S = S
  obtain c where c: raw-trail (rough-state-of (do-full1-cp-step S)) = c @ raw-trail (rough-state-of S)
    using do-full1-cp-step-neq-raw-trail-increase by auto

  moreover have raw-trail (rough-state-of (do-full1-cp-step S)) = raw-trail (rough-state-of S)
    using arg-cong[OF H, of  $\lambda S. \text{raw-trail (rough-state-of S)}$ ] by simp
  finally have c = [] by blast
  then have do-full1-cp-step S = S using assms by auto
}
moreover {
  assume confl: raw-conflicting (rough-state-of ?T) = None and neq: do-other-step' S  $\neq$  S
  obtain c where
    c: raw-trail (rough-state-of (do-full1-cp-step ?T)) = c @ raw-trail (rough-state-of ?T) and
    nm:  $\forall m \in \text{set } c. \neg \text{is-decided } m$ 
    using do-full1-cp-step-neq-raw-trail-increase by auto
  have length (filter is-decided (raw-trail (rough-state-of (do-full1-cp-step ?T))))
    = length (filter is-decided (raw-trail (rough-state-of ?T))) using nm unfolding c by force
  moreover have length (filter is-decided (raw-trail (rough-state-of S)))
     $\neq$  length (filter is-decided (raw-trail (rough-state-of ?T)))
    using do-other-step-not-raw-conflicting-one-more-decide[OF - neq]
    do-other-step-not-raw-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 cdclW-cp (toS (rough-state-of S)) S'
  then have False
    using do-full1-cp-step-full[of S] unfolding full-def S rtranclp-unfold full1-def
    by (smt assms do-cdclW-stgy-step-def tranclpD)
}
moreover {
  fix S' S''
  assume cdclW-o (toS (rough-state-of S)) S' and
    no-step propagate (toS (rough-state-of S)) and
    no-step conflict (toS (rough-state-of S)) and
    full cdclW-cp S' S''

```

```

then have False
  using assms unfolding do-cdclW-stgy-step-def
  by (smt cdclW-all-struct-inv-rough-state do-full1-cp-step-do-other-step'-normal-form
      do-other-step-no rough-state-of-do-other-step')
}
ultimately show ?thesis using assms by (force simp: cdclW-cp.simps cdclW-stgy.simps)
qed

```

```

lemma toS-rough-state-of-state-of-rough-state-from-init-state-of[simp]:
  toS (rough-state-of (state-of (rough-state-from-init-state-of S)))
    = toS (rough-state-from-init-state-of S)
  using rough-state-from-init-state-of[of S] by (auto simp add: state-of-inverse)

```

```

lemma cdclW-cp-is-rtrancp-cdclW: cdclW-cp S T  $\implies$  cdclW** S T
  apply (induction rule: cdclW-cp.induct)
  using conflict apply blast
  using propagate by blast

```

```

lemma rtrancp-cdclW-cp-is-rtrancp-cdclW: cdclW-cp** S T  $\implies$  cdclW** S T
  apply (induction rule: rtrancp-induct)
  apply simp
  by (fastforce dest!: cdclW-cp-is-rtrancp-cdclW)

```

```

lemma cdclW-stgy-is-rtrancp-cdclW:
  cdclW-stgy S T  $\implies$  cdclW** S T
  apply (induction rule: cdclW-stgy.induct)
  using cdclW-stgy.conflict' rtrancp-cdclW-stgy-rtrancp-cdclW apply blast
  unfolding full-def by (fastforce dest!:other rtrancp-cdclW-cp-is-rtrancp-cdclW)

```

```

lemma cdclW-stgy-init-raw-init-clss:
  cdclW-stgy S T  $\implies$  cdclW-M-level-inv S  $\implies$  raw-init-clss S = raw-init-clss T
  using cdclW-stgy-no-more-init-clss by blast

```

```

lemma clauses-toS-rough-state-of-do-cdclW-stgy-step[simp]:
  raw-init-clss (toS (rough-state-of (do-cdclW-stgy-step (state-of (rough-state-from-init-state-of S))))))
    = raw-init-clss (toS (rough-state-from-init-state-of S)) (is - = raw-init-clss (toS ?S))
  apply (cases do-cdclW-stgy-step (state-of ?S) = state-of ?S)
  apply simp
  by (metis cdclW-all-struct-inv-def cdclW-all-struct-inv-rough-state cdclW-stgy-no-more-init-clss
      do-cdclW-stgy-step toS-rough-state-of-state-of-rough-state-from-init-state-of)

```

```

lemma rough-state-from-init-state-of-do-cdclW-stgy-step'[code abstract]:
  rough-state-from-init-state-of (do-cdclW-stgy-step' S) =
    rough-state-of (do-cdclW-stgy-step (id-of-I-to S))

```

```

proof -
  let ?S = (rough-state-from-init-state-of S)
  have cdclW-stgy** (S0-cdclW (raw-init-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-cdcl_W-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-cdcl_W-stgy S =
 (let T = do-cdcl_W-stgy-step' S in
 if T = S then S else do-all-cdcl_W-stgy T)

by fast+

termination

proof (relation {(T, S).
 (cdcl_W-measure (toS (rough-state-from-init-state-of T)),
 cdcl_W-measure (toS (rough-state-from-init-state-of S)))
 ∈ le_{rn} less-than 3}, goal-cases)

case 1

show ?case by (rule wf-if-measure-f) (auto intro!: wf-le_{rn} 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: cdcl_W-stgy** (S0-cdcl_W (raw-init-clss (toS ?S))) (toS ?S)

using rough-state-from-init-state-of[of S] by auto

moreover have cdcl_W-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 state-of-inverse by fastforce

then have diff: do-cdcl_W-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-cdcl_W-stgy-step')

have rough-state-of (do-cdcl_W-stgy-step (state-of (rough-state-from-init-state-of S)))
 = rough-state-from-init-state-of (do-cdcl_W-stgy-step' S)

by (simp add: id-of-I-to-def rough-state-from-init-state-of-do-cdcl_W-stgy-step')

then show ?thesis

using do-cdcl_W-stgy-step T diff unfolding id-of-I-to-def do-cdcl_W-stgy-step by fastforce

qed

moreover

have cdcl_W-all-struct-inv (toS (rough-state-from-init-state-of S))

using rough-state-from-init-state-of[of S] by auto

then have cdcl_W-all-struct-inv (S0-cdcl_W (raw-init-clss (toS (rough-state-from-init-state-of S))))

by (cases rough-state-from-init-state-of S)

(auto simp add: cdcl_W-all-struct-inv-def distinct-cdcl_W-state-def)

ultimately show ?case

using tranclp-cdcl_W-stgy-S0-decreasing

by (auto intro!: cdcl_W-stgy-step-decreasing[of - - S0-cdcl_W (raw-init-clss (toS ?S))]
 simp del: cdcl_W-measure.simps)

qed

thm do-all-cdcl_W-stgy.induct

lemma do-all-cdcl_W-stgy-induct:

(∧S. (do-cdcl_W-stgy-step' S ≠ S ⇒ P (do-cdcl_W-stgy-step' S)) ⇒ P S) ⇒ P a0

using do-all-cdcl_W-stgy.induct by metis

lemma no-step-cdcl_W-stgy-cdcl_W-all:


```

fixes  $S :: 'a \text{ cdcl}_W\text{-state-inv-from-init-state}$ 
shows  $\text{no-step cdcl}_W\text{-stgy (toS (rough-state-from-init-state-of (do-all-cdcl}_W\text{-stgy S)))}$ 
apply ( $\text{induction } S \text{ rule: do-all-cdcl}_W\text{-stgy-induct}$ )
apply ( $\text{rename-tac } S, \text{ case-tac do-cdcl}_W\text{-stgy-step' } S \neq S$ )
proof –
  fix  $Sa :: 'a \text{ cdcl}_W\text{-state-inv-from-init-state}$ 
  assume  $a1: \neg \text{do-cdcl}_W\text{-stgy-step' } Sa \neq Sa$ 
  { fix  $pp$ 
    have ( $\text{if True then } Sa \text{ else do-all-cdcl}_W\text{-stgy } Sa$ ) =  $\text{do-all-cdcl}_W\text{-stgy } Sa$ 
      using  $a1$  by  $\text{auto}$ 
    then have  $\neg \text{cdcl}_W\text{-stgy (toS (rough-state-from-init-state-of (do-all-cdcl}_W\text{-stgy } Sa)))$   $pp$ 
      using  $a1$  by ( $\text{metis (no-types) do-cdcl}_W\text{-stgy-step-no id-of-I-to-def}$ 
         $\text{rough-state-from-init-state-of-do-cdcl}_W\text{-stgy-step' rough-state-of-inverse}$ ) }
    then show  $\text{no-step cdcl}_W\text{-stgy (toS (rough-state-from-init-state-of (do-all-cdcl}_W\text{-stgy } Sa)))$ 
      by  $\text{fastforce}$ 
  }
next
  fix  $Sa :: 'a \text{ cdcl}_W\text{-state-inv-from-init-state}$ 
  assume  $a1: \text{do-cdcl}_W\text{-stgy-step' } Sa \neq Sa$ 
     $\implies \text{no-step cdcl}_W\text{-stgy (toS (rough-state-from-init-state-of (do-all-cdcl}_W\text{-stgy (do-cdcl}_W\text{-stgy-step' } Sa))))$ 
  assume  $a2: \text{do-cdcl}_W\text{-stgy-step' } Sa \neq Sa$ 
  have  $\text{do-all-cdcl}_W\text{-stgy } Sa = \text{do-all-cdcl}_W\text{-stgy (do-cdcl}_W\text{-stgy-step' } Sa)$ 
    by ( $\text{metis (full-types) do-all-cdcl}_W\text{-stgy.simps}$ )
  then show  $\text{no-step cdcl}_W\text{-stgy (toS (rough-state-from-init-state-of (do-all-cdcl}_W\text{-stgy } Sa)))$ 
    using  $a2 \ a1$  by  $\text{presburger}$ 
qed

lemma  $\text{do-all-cdcl}_W\text{-stgy-is-rtrancpl-cdcl}_W\text{-stgy:}$ 
 $\text{cdcl}_W\text{-stgy}^* \text{ (toS (rough-state-from-init-state-of } S))$ 
 $\text{(toS (rough-state-from-init-state-of (do-all-cdcl}_W\text{-stgy } S)))$ 
proof ( $\text{induction } S \text{ rule: do-all-cdcl}_W\text{-stgy-induct}$ )
  case ( $1 \ S$ ) note  $IH = \text{this}(1)$ 
  show  $?case$ 
    proof ( $\text{cases do-cdcl}_W\text{-stgy-step' } S = S$ )
      case  $\text{True}$ 
        then show  $?thesis$  by  $\text{simp}$ 
      next
        case  $\text{False}$ 
        have  $f2: \text{do-cdcl}_W\text{-stgy-step (id-of-I-to } S) = \text{id-of-I-to } S \longrightarrow$ 
           $\text{rough-state-from-init-state-of (do-cdcl}_W\text{-stgy-step' } S)$ 
           $= \text{rough-state-of (state-of (rough-state-from-init-state-of } S))$ 
          using  $\text{rough-state-from-init-state-of-do-cdcl}_W\text{-stgy-step'}$ 
          by ( $\text{simp add: id-of-I-to-def rough-state-from-init-state-of-do-cdcl}_W\text{-stgy-step'}$ )
        have  $f3: \text{do-all-cdcl}_W\text{-stgy } S = \text{do-all-cdcl}_W\text{-stgy (do-cdcl}_W\text{-stgy-step' } S)$ 
          by ( $\text{metis (full-types) do-all-cdcl}_W\text{-stgy.simps}$ )
        have  $\text{cdcl}_W\text{-stgy (toS (rough-state-from-init-state-of } S))$ 
           $\text{(toS (rough-state-from-init-state-of (do-cdcl}_W\text{-stgy-step' } S)))}$ 
           $= \text{cdcl}_W\text{-stgy (toS (rough-state-of (id-of-I-to } S)))}$ 
           $\text{(toS (rough-state-of (do-cdcl}_W\text{-stgy-step (id-of-I-to } S))))}$ 
          using  $\text{rough-state-from-init-state-of-do-cdcl}_W\text{-stgy-step'}$ 
           $\text{toS-rough-state-of-state-of-rough-state-from-init-state-of}$ 
          by ( $\text{simp add: id-of-I-to-def rough-state-from-init-state-of-do-cdcl}_W\text{-stgy-step'}$ )
        then show  $?thesis$ 
          using  $f3 \ f2 \ IH \ \text{do-cdcl}_W\text{-stgy-step}$  by  $\text{fastforce}$ 
    }
qed
qed

```

Final theorem:

lemma *DPLL-tot-correct*:

assumes

r: *rough-state-from-init-state-of* (*do-all-cdcl_W-stgy* (*state-from-init-state-of* ($\llbracket \cdot \rrbracket$, *map remdups* *N*, $\llbracket \cdot \rrbracket$, 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*: *cdcl_W-all-struct-inv* (*toS* ($\llbracket \cdot \rrbracket$, *map remdups* *N*, $\llbracket \cdot \rrbracket$, 0, None))

unfolding *cdcl_W-all-struct-inv-def* *distinct-cdcl_W-state-def* *distinct-mset-set-def* **by** *auto*

then have *S0*: *rough-state-of* (*state-of* ($\llbracket \cdot \rrbracket$, *map remdups* *N*, $\llbracket \cdot \rrbracket$, 0, None))

= ($\llbracket \cdot \rrbracket$, *map remdups* *N*, $\llbracket \cdot \rrbracket$, 0, None) **by** *simp*

have 1: *full cdcl_W-stgy* (*toS* ($\llbracket \cdot \rrbracket$, ?*N*, $\llbracket \cdot \rrbracket$, 0, None)) (*toS S*)

unfolding *full-def* **apply** *rule*

using *do-all-cdcl_W-stgy-is-rtranclp-cdcl_W-stgy*[*of*

state-from-init-state-of ($\llbracket \cdot \rrbracket$, *map remdups* *N*, $\llbracket \cdot \rrbracket$, 0, None)] *inv*

no-step-cdcl_W-stgy-cdcl_W-all

apply (*auto simp del: do-all-cdcl_W-stgy.simps simp: state-from-init-state-of-inverse* *r[symmetric] comp-def*)[]

using *do-all-cdcl_W-stgy-is-rtranclp-cdcl_W-stgy*[*of*

state-from-init-state-of ($\llbracket \cdot \rrbracket$, *map remdups* *N*, $\llbracket \cdot \rrbracket$, 0, None)] *inv*

no-step-cdcl_W-stgy-cdcl_W-all

by (*force simp: state-from-init-state-of-inverse r[symmetric] comp-def*)

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 *cdcl_W-all-struct-inv* (*toS S*)

by (*metis* (*no-types*) *cdcl_W-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-l M'*)

unfolding *cdcl_W-all-struct-inv-def* *cdcl_W-M-level-inv-def* *S[symmetric]* **by** *auto*

moreover

have *raw-init-clss* (*toS* ($\llbracket \cdot \rrbracket$, ?*N*, $\llbracket \cdot \rrbracket$, 0, None)) = *raw-init-clss* (*toS S*)

apply (*rule rtranclp-cdcl_W-stgy-no-more-init-clss*)

using 1 **unfolding** *full-def* **by** (*auto simp add: rtranclp-cdcl_W-stgy-rtranclp-cdcl_W*)

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-cdcl_W-stgy-final-state-conclusive* **unfolding** *N'* **apply** *rule*

using 1 **apply** *simp*

using 2 **apply** *simp*

using 3 **apply** *simp*

using *S[symmetric]* *N'* **apply** *auto*[1]

using *S[symmetric]* *N'* *cons* **by** (*fastforce simp: true-annots-true-cl*s)

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-Abstract-Clause-Representation
imports Main Partial-Clausal-Logic
begin

```

```

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

```

7.1.6 Abstract Clause Representation

We will abstract the representation of clause and clauses via two locales. We expect our representation to behave like multiset, but the internal representation can be done using list or whatever other representation.

We assume the following:

- there is an equivalent to adding and removing a literal and to taking the union of clauses.

```

locale raw-cls =
  fixes
    mset-cls :: 'cls  $\Rightarrow$  'v clause
begin
end

```

Instantiation of the previous locale, in an unnamed context to avoid polluting with simp rules

```

context
begin
  interpretation list-cls: raw-cls mset
    by unfold-locales

  interpretation cls-cls: raw-cls id
    by unfold-locales
end

```

end

Over the abstract clauses, we have the following properties:

- We can insert a clause
- We can take the union (used only in proofs for the definition of *clauses*)
- there is an operator indicating whether the abstract clause is contained or not
- if a concrete clause is contained the abstract clauses, then there is an abstract clause

```

locale raw-clss =
  raw-cls mset-cls
  for
    mset-cls :: 'cls  $\Rightarrow$  'v clause +
  fixes
    mset-clss :: 'clss  $\Rightarrow$  'v clauses and
    in-clss :: 'cls  $\Rightarrow$  'clss  $\Rightarrow$  bool and
    insert-clss :: 'cls  $\Rightarrow$  'clss  $\Rightarrow$  'clss
  assumes
    insert-clss[simp]: mset-clss (insert-clss L C) = mset-clss C + {#mset-cl L#} and

```

```

    in-clss-mset-clss[dest]: in-clss a C  $\implies$  mset-cls a  $\in$  # mset-clss C and
    in-mset-clss-exists-preimage: b  $\in$  # mset-clss C  $\implies \exists b'. \text{in-clss } b' C \wedge \text{mset-cls } b' = b$ 
begin

end

experiment
begin
  fun remove-first where
    remove-first - [] = [] |
    remove-first C (C' # L) = (if mset C = mset C' then L else C' # remove-first C L)

  lemma mset-map-mset-remove-first:
    mset (map mset (remove-first a C)) = remove1-mset (mset a) (mset (map mset C))
    by (induction C) (auto simp: ac-simps remove1-mset-single-add)

  interpretation clss-clss: raw-clss id
    id op  $\in$  #  $\lambda L. C. C + \{\#L\# \}$ 
    by unfold-locales (auto simp: ac-simps)

  interpretation list-clss: raw-clss mset
     $\lambda L. \text{mset (map mset L)}$   $\lambda L. C. L \in \text{set } C \text{ op } \#$ 
    by unfold-locales (auto simp: ac-simps union-mset-list mset-map-mset-remove-first ex-mset)
end

end

theory CDCL-W-Abstract-State
imports CDCL-Abstract-Clause-Representation List-More CDCL-W-Level Wellfounded-More
        CDCL-WNOT CDCL-Abstract-Clause-Representation

begin

```

7.2 Weidenbach's CDCL with Abstract Clause Representation

We first instantiate the locale of Weidenbach's locale. Then we define another abstract state: the goal of this state is to be used for implementations. We add more assumptions on the function about the state. For example *cons-trail* is restricted to undefined literals.

7.2.1 Instantiation of the Multiset Version

```

type-synonym 'v cdclW-mset = ('v, 'v clause) ann-lit list  $\times$ 
  'v clauses  $\times$ 
  'v clauses  $\times$ 
  nat  $\times$  'v clause option

```

We use definition, otherwise we could not use the simplification theorems we have already shown.

```

definition trail :: 'v cdclW-mset  $\Rightarrow$  ('v, 'v clause) ann-lit list where
  trail  $\equiv \lambda(M, -). M$ 

```

```

definition init-clss :: 'v cdclW-mset  $\Rightarrow$  'v clauses where
  init-clss  $\equiv \lambda(-, N, -). N$ 

```

```

definition learned-clss :: 'v cdclW-mset  $\Rightarrow$  'v clauses where
  learned-clss  $\equiv \lambda(-, -, U, -). U$ 

```

definition *backtrack-lvl* :: 'v *cdcl_W-mset* \Rightarrow nat **where**
backtrack-lvl $\equiv \lambda(-, -, -, k, -). k$

definition *conflicting* :: 'v *cdcl_W-mset* \Rightarrow 'v *clause option* **where**
conflicting $\equiv \lambda(-, -, -, -, C). C$

definition *cons-trail* :: ('v, 'v *clause*) *ann-lit* \Rightarrow 'v *cdcl_W-mset* \Rightarrow 'v *cdcl_W-mset* **where**
cons-trail $\equiv \lambda L (M, R). (L \# M, R)$

definition *tl-trail* **where**
tl-trail $\equiv \lambda(M, R). (tl\ M, R)$

definition *add-learned-cls* **where**
add-learned-cls $\equiv \lambda C (M, N, U, R). (M, N, \{\#C\# \} + U, R)$

definition *remove-cls* **where**
remove-cls $\equiv \lambda C (M, N, U, R). (M, removeAll-mset\ C\ N, removeAll-mset\ C\ U, R)$

definition *update-backtrack-lvl* **where**
update-backtrack-lvl $\equiv \lambda k (M, N, U, -, D). (M, N, U, k, D)$

definition *update-conflicting* **where**
update-conflicting $\equiv \lambda D (M, N, U, k, -). (M, N, U, k, D)$

definition *init-state* **where**
init-state $\equiv \lambda N. ([], N, \{\#\}, 0, None)$

lemmas *cdcl_W-mset-state* = *trail-def cons-trail-def tl-trail-def add-learned-cls-def*
remove-cls-def update-backtrack-lvl-def update-conflicting-def init-clss-def learned-clss-def
backtrack-lvl-def conflicting-def init-state-def

interpretation *cdcl_W-mset: state_W-ops* **where**

trail = *trail* **and**
init-clss = *init-clss* **and**
learned-clss = *learned-clss* **and**
backtrack-lvl = *backtrack-lvl* **and**
conflicting = *conflicting* **and**

cons-trail = *cons-trail* **and**
tl-trail = *tl-trail* **and**
add-learned-cls = *add-learned-cls* **and**
remove-cls = *remove-cls* **and**
update-backtrack-lvl = *update-backtrack-lvl* **and**
update-conflicting = *update-conflicting* **and**
init-state = *init-state*
.

interpretation *cdcl_W-mset: state_W* **where**

trail = *trail* **and**
init-clss = *init-clss* **and**
learned-clss = *learned-clss* **and**
backtrack-lvl = *backtrack-lvl* **and**
conflicting = *conflicting* **and**

cons-trail = *cons-trail* **and**

$tl_trail = tl_trail$ **and**
 $add_learned_cls = add_learned_cls$ **and**
 $remove_cls = remove_cls$ **and**
 $update_backtrack_lvl = update_backtrack_lvl$ **and**
 $update_conflicting = update_conflicting$ **and**
 $init_state = init_state$
by $unfold_locales$ ($auto$ $simp$: $cdcl_W$ - $mset$ - $state$)

interpretation $cdcl_W$ - $mset$: *conflict-driven-clause-learning_W* **where**

$trail = trail$ **and**
 $init_clss = init_clss$ **and**
 $learned_clss = learned_clss$ **and**
 $backtrack_lvl = backtrack_lvl$ **and**
 $conflicting = conflicting$ **and**

$cons_trail = cons_trail$ **and**
 $tl_trail = tl_trail$ **and**
 $add_learned_cls = add_learned_cls$ **and**
 $remove_cls = remove_cls$ **and**
 $update_backtrack_lvl = update_backtrack_lvl$ **and**
 $update_conflicting = update_conflicting$ **and**
 $init_state = init_state$
by $unfold_locales$ $auto$

lemma $cdcl_W$ - $mset$ - $state$ - eq - eq : $cdcl_W$ - $mset$. $state$ - $eq = (op =)$

apply ($intro$ ext)
unfolding $cdcl_W$ - $mset$. $state$ - eq - def
by ($auto$ $simp$: $cdcl_W$ - $mset$ - $state$)

notation $cdcl_W$ - $mset$. $state$ - eq ($\text{infix } \sim_m 49$)

7.2.2 Abstract Relation and Relation Theorems

This locales makes the lifting from the relation defined with multiset R and the version with an abstract state R - abs . We are lifting many different relations (each rule and the the strategy).

locale $relation$ - $implied$ - $relation$ - $abs =$

fixes

$R :: 'v\ cdcl_W$ - $mset \Rightarrow 'v\ cdcl_W$ - $mset \Rightarrow bool$ **and**
 R - $abs :: 'st \Rightarrow 'st \Rightarrow bool$ **and**
 $state :: 'st \Rightarrow 'v\ cdcl_W$ - $mset$ **and**
 $inv :: 'v\ cdcl_W$ - $mset \Rightarrow bool$

assumes

$relation$ - $compatible$ - $state$:

$inv\ (state\ S) \Longrightarrow R$ - $abs\ S\ T \Longrightarrow R\ (state\ S)\ (state\ T)$ **and**

$relation$ - $compatible$ - abs :

$\bigwedge S\ S'\ T. inv\ S \Longrightarrow S \sim_m state\ S' \Longrightarrow R\ S\ T \Longrightarrow \exists U. R$ - $abs\ S'\ U \wedge T \sim_m state\ U$ **and**

$relation$ - $invariant$:

$\bigwedge S\ T. R\ S\ T \Longrightarrow inv\ S \Longrightarrow inv\ T$ **and**

$relation$ - abs - $right$ - $compatible$:

$\bigwedge S\ T\ U. inv\ (state\ S) \Longrightarrow R$ - $abs\ S\ T \Longrightarrow state\ T \sim_m state\ U \Longrightarrow R$ - $abs\ S\ U$

begin

lemma $relation$ - $compatible$ - eq :

assumes

inv : $inv\ (state\ S)$ **and**

$abs: R-abs\ S\ T$ **and**
 $SS': state\ S \sim_m state\ S'$ **and**
 $TT': state\ T \sim_m state\ T'$
shows $R-abs\ S'\ T'$
proof –
have $R\ (state\ S)\ (state\ T)$
using *relation-compatible-state inv abs* **by** *blast*
then obtain U **where** $S'U: R-abs\ S'\ U$ **and** $TU: state\ T \sim_m state\ U$
using *relation-compatible-abs[OF inv SS']* **by** *blast*
then show *?thesis*
using *relation-abs-right-compatible[OF - S'U, of T] TT' inv SS'[unfolded cdcl_W-mset-state-eq-eq]*
cdcl_W-mset.state-eq-trans[of state T' state T state U]
by (*auto simp add: cdcl_W-mset.state-eq-sym*)
qed

lemma *rtrancpl-relation-invariant:*
 $R^{++}\ S\ T \implies inv\ S \implies inv\ T$
by (*induction rule: trancpl-induct*) (*auto simp: relation-invariant*)

lemma *rtrancpl-abs-rtrancpl:*
 $R-abs^{**}\ S\ T \implies inv\ (state\ S) \implies R^{**}\ (state\ S)\ (state\ T)$
apply (*induction rule: rtrancpl-induct*)
apply *simp*
by (*metis relation-compatible-state rtrancpl.simps rtrancplD rtrancpl-relation-invariant*)

lemma *trancpl-relation-trancpl-relation-abs-compatible:*
fixes $S :: 'st$
assumes
 $R: R^{++}\ (state\ S)\ T$ **and**
 $inv: inv\ (state\ S)$
shows $\exists U. R-abs^{++}\ S\ U \wedge T \sim_m state\ U$
using R
proof (*induction rule: trancpl-induct*)
case (*base T*)
then show *?case*
using *relation-compatible-abs[of state S S T] inv* **by** *auto*
next
case (*step T U*) **note** $st = this(1)$ **and** $R = this(2)$ **and** $IH = this(3)$
obtain V **where**
 $SV: R-abs^{++}\ S\ V$ **and** $TV: T \sim_m state\ V$
using IH **by** *auto*
then obtain W **where**
 $VW: R-abs\ V\ W$ **and** $UW: U \sim_m state\ W$
using *relation-compatible-abs[OF - TV R] inv rtrancpl-relation-invariant[OF st]* **by** *blast*
have $R-abs^{++}\ S\ W$
using $SV\ VW$ **by** *auto*
then show *?case* **using** UW **by** *blast*
qed

lemma *rtrancpl-relation-rtrancpl-relation-abs-compatible:*
fixes $S :: 'st$
assumes
 $R: R^{**}\ (state\ S)\ T$ **and**
 $inv: inv\ (state\ S)$
shows $\exists U. R-abs^{**}\ S\ U \wedge T \sim_m state\ U$

```

using  $R$  inv by (auto simp: rtrncpl-unfold dest: trncpl-relation-trncpl-relation-abs-compatible)

lemma no-step-iff:
   $\text{inv} (\text{state } S) \implies \text{no-step } R (\text{state } S) \longleftrightarrow \text{no-step } R\text{-abs } S$ 
  using relation-compatible-state relation-compatible-abs cdclW-mset.state-eq-ref
  by blast

lemma trncpl-relation-compatible-eq-and-inv:
  assumes
     $\text{inv}: \text{inv} (\text{state } S)$  and
     $\text{st}: R\text{-abs}^{++} S T$  and
     $SS': \text{state } S \sim_m \text{state } S'$  and
     $TU: \text{state } T \sim_m \text{state } U$ 
  shows  $R\text{-abs}^{++} S' U \wedge \text{inv} (\text{state } U)$ 
  using st TU
proof (induction arbitrary: U rule: trncpl-induct)
  case (base T)
  moreover then have  $\text{inv} (\text{state } U)$ 
    by (metis (full-types) cdclW-mset-state-eq-eq inv relation-compatible-state relation-invariant)
  ultimately show ?case
    using relation-compatible-eq[of S T S' U] SS' inv
    by (auto simp: trncpl.r-into-trncpl)
next
  case (step T T') note st = this(1) and R = this(2) and IH = this(3) and TU = this(4)
  have  $R\text{-abs}^{++} S' T$  and  $\text{inv} T: \text{inv} (\text{state } T)$  using IH[of T] by auto
  moreover have  $R\text{-abs } T U$ 
    using relation-compatible-eq[of T T' T U] R TU inv rtrncpl-relation-invariant invT by simp
  moreover have  $\text{inv} (\text{state } U)$ 
    using calculation(3) invT relation-compatible-state relation-invariant by blast
  ultimately show ?case by auto
qed

lemma
  assumes
     $\text{inv}: \text{inv} (\text{state } S)$  and
     $\text{st}: R\text{-abs}^{++} S T$  and
     $SS': \text{state } S \sim_m \text{state } S'$  and
     $TU: \text{state } T \sim_m \text{state } U$ 
  shows
    trncpl-relation-compatible-eq:  $R\text{-abs}^{++} S' U$  and
    trncpl-relation-abs-invariant:  $\text{inv} (\text{state } U)$ 
    using trncpl-relation-compatible-eq-and-inv[OF assms] by blast+

lemma trncpl-abs-trncpl:  $R\text{-abs}^{++} S T \implies \text{inv} (\text{state } S) \implies R^{++} (\text{state } S) (\text{state } T)$ 
  apply (induction rule: trncpl-induct)
  apply (auto simp add: relation-compatible-state)[]
  apply clarsimp
  apply (erule trncpl.trncpl-into-trncpl)
  using relation-compatible-state trncpl-relation-abs-invariant by blast

lemma full1-iff:
  assumes  $\text{inv}: \text{inv} (\text{state } S)$ 
  shows full1 R (state S) (state T)  $\longleftrightarrow$  full1 R-abs S T (is ?R  $\longleftrightarrow$  ?R-abs)
proof
  assume ?R
  then have st:  $R^{++} (\text{state } S) (\text{state } T)$  and ns: no-step R (state T) unfolding full1-def by auto

```



```

have invT: inv (state T)
  using inv rtracp-relation-invariant st by blast
then have R-abs++ S T
  using tracp-relation-tracp-relation-abs-compatible[OF st] inv
  tracp-relation-compatible-eq[of S - S T] cdclW-mset.state-eq-sym by blast
moreover have no-step R-abs T
  using ns inv no-step-iff invT by blast
ultimately show ?R-abs
  unfolding full1-def by blast
next
assume ?R-abs
then have st: R-abs++ S T and ns: no-step R-abs T unfolding full1-def by auto
have R++ (state S) (state T)
  using st tracp-abs-tracp inv by blast
moreover
  have invT: inv (state T)
    using inv tracp-relation-abs-invariant st by blast
  then have no-step R (state T)
    using ns inv no-step-iff by blast
ultimately show ?R
  unfolding full1-def by blast
qed

```

lemma full1-iff-compatible:

```

assumes inv: inv (state S) and SS': S' ~m state S and TT': T' ~m state T
shows full1 R S' T'  $\longleftrightarrow$  full1 R-abs S T (is ?R  $\longleftrightarrow$  ?R-abs)
using full1-iff assms unfolding cdclW-mset-state-eq-eq by simp

```

lemma full-if-full-abs:

```

assumes inv (state S) and full R-abs S T
shows full R (state S) (state T)
using assms full1-iff cdclW-mset-state-eq-eq relation-compatible-abs
unfolding full-unfold by blast

```

The converse does *not* hold, since we cannot prove that $S = T$ given $\text{state } S = \text{state } T$.

lemma full-abs-if-full:

```

assumes inv (state S) and full R (state S) (state T)
shows full R-abs S T  $\vee$  (state S ~m state T  $\wedge$  no-step R (state S))
using assms full1-iff relation-compatible-abs unfolding full-unfold by auto

```

lemma full-exists-full-abs:

```

assumes inv: inv (state S) and full: full R (state S) T
obtains U where full R-abs S U and T ~m state U

```

proof –

consider

```

(0) state S = T and no-step R (state S) |
(full1) full1 R (state S) T

```

using full unfolding full-unfold cdcl_W-mset-state-eq-eq by fast

then show ?thesis

proof cases

case 0

then show ?thesis using that[of S] unfolding full-def

using cdcl_W-mset.state-eq-ref inv relation-compatible-state rtracp.rtracp-refl by blast

next

case full1

then obtain U where

```

     $R\text{-abs}^{++} S U$  and  $T \sim_m \text{state } U$ 
    using trancpl-relation-trancpl-relation-abs-compatible inv unfolding full1-def
    by blast
  then show ?thesis
    using full1 that[of U] full1-iff[OF inv] full1-is-full full-def
    unfolding cdclW-mset-state-eq-eq by blast
qed
qed

lemma full1-exists-full1-abs:
  assumes inv: inv (state S) and full1: full1 R (state S) T
  obtains U where full1 R-abs S U and T ~m state U
proof -
  obtain U where
     $R\text{-abs}^{++} S U$  and  $T \sim_m \text{state } U$ 
    using trancpl-relation-trancpl-relation-abs-compatible inv full1 unfolding full1-def
    by blast
  then show ?thesis
    using full1 that[of U] full1-iff[OF inv] unfolding cdclW-mset-state-eq-eq by blast
qed

lemma full1-right-compatible:
  assumes inv (state S) and
    full1: full1 R-abs S T and TV: state T ~m state V
  shows full1 R-abs S V
  by (metis (full-types) TV assms(1) cdclW-mset-state-eq-eq full1 full1-iff)

lemma full-right-compatible:
  assumes inv: inv (state S) and
    full-ST: full R-abs S T and TU: state T ~m state U
  shows full R-abs S U  $\vee$  (S = T  $\wedge$  no-step R-abs S)
proof -
  consider
    (0)  $S = T$  and no-step R-abs T |
    (full1) full1 R-abs S T
  using full-ST unfolding full-unfold by blast
  then show ?thesis
    proof cases
      case full1
        then show ?thesis
          using full1-right-compatible[OF inv, of T U] TU full-unfold by blast
      next
        case 0
          then show ?thesis by fast
    qed
  qed
qed

end

locale relation-relation-abs =
  fixes
     $R :: 'v \text{ cdcl}_W\text{-mset} \Rightarrow 'v \text{ cdcl}_W\text{-mset} \Rightarrow \text{bool}$  and
     $R\text{-abs} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$  and
     $\text{state} :: 'st \Rightarrow 'v \text{ cdcl}_W\text{-mset} \Rightarrow \text{bool}$  and
     $\text{inv} :: 'v \text{ cdcl}_W\text{-mset} \Rightarrow \text{bool}$ 
  assumes

```

```

relation-compatible-state:
  inv (state S)  $\implies$  R (state S) (state T)  $\longleftrightarrow$  R-abs S T and
relation-compatible-abs:
   $\bigwedge S S' T. \text{inv } S \implies S \sim_m \text{state } S' \implies R S T \implies \exists U. R\text{-abs } S' U \wedge T \sim_m \text{state } U$  and
relation-invariant:
   $\bigwedge S T. R S T \implies \text{inv } S \implies \text{inv } T$ 
begin

lemma relation-compatible-eq:
  inv (state S)  $\implies$  R-abs S T  $\implies$  state S  $\sim_m$  state S'  $\implies$  state T  $\sim_m$  state T'  $\implies$  R-abs S' T'
  by (simp add: cdclW-mset-state-eq-eq relation-compatible-state[symmetric])

lemma relation-right-compatible:
  inv (state S)  $\implies$  R-abs S T  $\implies$  state T  $\sim_m$  state U  $\implies$  R-abs S U
  by (simp add: cdclW-mset-state-eq-eq relation-compatible-state[symmetric])

sublocale relation-implied-relation-abs
  apply unfold-locales
  using relation-compatible-eq relation-compatible-state relation-compatible-abs relation-invariant
  relation-right-compatible by blast+

end

```

7.2.3 The State

We will abstract the representation of clause and clauses via two locales. We expect our representation to behave like multiset, but the internal representation can be done using list or whatever other representation.

```

locale abs-stateW-ops =
  raw-clss mset-cls
  mset-clss in-clss insert-clss
  +
  raw-cls mset-ccls
for
  — Clause
  mset-cls :: 'cls  $\Rightarrow$  'v clause and

  — Multiset of Clauses
  mset-clss :: 'clss  $\Rightarrow$  'v clauses and
  in-clss :: 'cls  $\Rightarrow$  'clss  $\Rightarrow$  bool and
  insert-clss :: 'cls  $\Rightarrow$  'clss  $\Rightarrow$  'clss and

  mset-ccls :: 'ccls  $\Rightarrow$  'v clause
  +
fixes
  ccls-of-cls :: 'cls  $\Rightarrow$  'ccls and
  cls-of-ccls :: 'ccls  $\Rightarrow$  'cls and

  conc-trail :: 'st  $\Rightarrow$  ('v, 'v clause) ann-lits and
  hd-raw-conc-trail :: 'st  $\Rightarrow$  ('v, 'cls) ann-lit and
  raw-clauses :: 'st  $\Rightarrow$  'clss and
  conc-backtrack-lvl :: 'st  $\Rightarrow$  nat and
  raw-conc-conflicting :: 'st  $\Rightarrow$  'ccls option and

```

```

conc-learned-clss :: 'st  $\Rightarrow$  'v clauses and

cons-conc-trail :: ('v, 'cls) ann-lit  $\Rightarrow$  'st  $\Rightarrow$  'st and
tl-conc-trail :: 'st  $\Rightarrow$  'st and
add-conc-conflict-to-learned-clss :: 'st  $\Rightarrow$  'st and
remove-clss :: 'cls  $\Rightarrow$  'st  $\Rightarrow$  'st and
update-conc-backtrack-lvl :: nat  $\Rightarrow$  'st  $\Rightarrow$  'st and
mark-conflicting :: 'ccls  $\Rightarrow$  'st  $\Rightarrow$  'st and
reduce-conc-trail-to :: ('v, 'v clause) ann-lits  $\Rightarrow$  'st  $\Rightarrow$  'st and
resolve-conflicting :: 'v literal  $\Rightarrow$  'cls  $\Rightarrow$  'st  $\Rightarrow$  'st and

conc-init-state :: 'clss  $\Rightarrow$  'st and
restart-state :: 'st  $\Rightarrow$  'st
assumes
  mset-ccls-ccls-of-clss[simp]:
    mset-ccls (ccls-of-clss C) = mset-clss C and
  mset-clss-clss-of-ccls[simp]:
    mset-clss (clss-of-ccls D) = mset-ccls D and
  ex-mset-clss:  $\exists a. \text{mset-clss } a = E$ 
begin

fun mmset-of-mlit :: ('v, 'cls) ann-lit  $\Rightarrow$  ('v, 'v clause) ann-lit
  where
mmset-of-mlit (Propagated L C) = Propagated L (mset-clss C) |
mmset-of-mlit (Decided L) = Decided L

lemma lit-of-mmset-of-mlit[simp]:
  lit-of (mmset-of-mlit a) = lit-of a
  by (cases a) auto

lemma lit-of-mmset-of-mlit-set-lit-of-l[simp]:
  lit-of ' mmset-of-mlit ' set M' = lits-of-l M'
  by (induction M') auto

lemma map-mmset-of-mlit-true-annots-true-clss[simp]:
  map mmset-of-mlit M'  $\models_{as}$  C  $\longleftrightarrow$  M'  $\models_{as}$  C
  by (simp add: true-annots-true-clss lits-of-def)

definition conc-init-clss  $\equiv \lambda S. \text{mset-clss } (\text{raw-clauses } S) - \text{conc-learned-clss } S$ 
abbreviation conc-conflicting  $\equiv \lambda S. \text{map-option mset-ccls } (\text{raw-conc-conflicting } S)$ 

notation in-clss (infix ! $\in$ ! 50)
notation insert-clss (infix !++! 50)

abbreviation conc-clauses :: 'st  $\Rightarrow$  'v clauses where
conc-clauses S  $\equiv \text{mset-clss } (\text{raw-clauses } S)$ 

definition state :: 'st  $\Rightarrow$  'v cdclW-mset where
state = ( $\lambda S. (\text{conc-trail } S, \text{conc-init-clss } S, \text{conc-learned-clss } S, \text{conc-backtrack-lvl } S,$ 
  conc-conflicting S))

end

```

We are using an abstract state to abstract away the detail of the implementation: we do not need to know how the clauses are represented internally, we just need to know that they can be converted to multisets.

Weidenbach state is a five-tuple composed of:

1. the trail is a list of decided literals;
2. the initial set of clauses (that is not changed during the whole calculus);
3. the learned clauses (clauses can be added or remove);
4. the maximum level of the trail;
5. the conflicting clause (if any has been found so far).

There are two different clause representation: one for the conflicting clause (*'ccls*, standing for conflicting clause) and one for the initial and learned clauses (*'cls*, standing for clause). The representation of the clauses annotating literals in the trail is slightly different: being able to convert it to *'v CDCL-Abstract-Clause-Representation.clause* is enough (needed for function *hd-raw-conc-trail* below).

There are several axioms to state the independance of the different fields of the state: for example, adding a clause to the learned clauses does not change the trail.

We define the following operations on the elements

- trail: *cons-trail*, *tl-trail*, and *reduce-conc-trail-to*.
- initial set of clauses: a clause can be removed.
- learned clauses: *add-conc-conflict-to-learned-cls* moves the conflicting clause to the learned clauses.
- backtrack level: it can be arbitrary set.
- conflicting clause: there is *resolve-conflicting* that does a resolve step, *mark-conflicting* setting a conflict, and *add-conc-conflict-to-learned-cls* setting the conflicting clause to *None*.

To ease the representation, we consider the clauses all together, where some of them are learned. This eases representation like arrays where the initial set of clause is at the beginning and avoid having an explicit *op* \cup operator.

locale *abs-state_W* =
abs-state_W-ops
— functions for clauses:
mset-cls
mset-clss in-clss insert-clss

— functions for the conflicting clause:
mset-ccls

— Conversion between conflicting and non-conflicting
ccls-of-cls cls-of-ccls

— functions about the state:
— getter:
conc-trail hd-raw-conc-trail raw-clauses conc-backtrack-lvl
raw-conc-conflicting conc-learned-clss
— setter:

cons-conc-trail tl-conc-trail add-conc-confl-to-learned-cls remove-cls update-conc-backtrack-lvl
mark-conflicting reduce-conc-trail-to resolve-conflicting

— Some specific states:

conc-init-state

restart-state

for

mset-cls :: '*cls* ⇒ '*v clause* **and**

mset-clss :: '*clss* ⇒ '*v clauses* **and**

in-clss :: '*cls* ⇒ '*clss* ⇒ *bool* **and**

insert-clss :: '*cls* ⇒ '*clss* ⇒ '*clss* **and**

mset-ccls :: '*ccls* ⇒ '*v clause* **and**

ccls-of-cls :: '*cls* ⇒ '*ccls* **and**

cls-of-ccls :: '*ccls* ⇒ '*cls* **and**

conc-trail :: '*st* ⇒ ('*v*, '*v clause*) *ann-lits* **and**

hd-raw-conc-trail :: '*st* ⇒ ('*v*, '*cls*) *ann-lit* **and**

raw-clauses :: '*st* ⇒ '*clss* **and**

conc-backtrack-lvl :: '*st* ⇒ *nat* **and**

raw-conc-conflicting :: '*st* ⇒ '*ccls option* **and**

conc-learned-clss :: '*st* ⇒ '*v clauses* **and**

cons-conc-trail :: ('*v*, '*cls*) *ann-lit* ⇒ '*st* ⇒ '*st* **and**

tl-conc-trail :: '*st* ⇒ '*st* **and**

add-conc-confl-to-learned-cls :: '*st* ⇒ '*st* **and**

remove-cls :: '*cls* ⇒ '*st* ⇒ '*st* **and**

update-conc-backtrack-lvl :: *nat* ⇒ '*st* ⇒ '*st* **and**

mark-conflicting :: '*ccls* ⇒ '*st* ⇒ '*st* **and**

reduce-conc-trail-to :: ('*v*, '*v clause*) *ann-lits* ⇒ '*st* ⇒ '*st* **and**

resolve-conflicting :: '*v literal* ⇒ '*cls* ⇒ '*st* ⇒ '*st* **and**

conc-init-state :: '*clss* ⇒ '*st* **and**

restart-state :: '*st* ⇒ '*st* +

assumes

— Definition of *hd-raw-trail*:

hd-raw-conc-trail:

conc-trail *S* ≠ [] ⇒ *mmset-of-mlit* (*hd-raw-conc-trail* *S*) = *hd* (*conc-trail* *S*) **and**

cons-conc-trail:

∧ *S'*. *undefined-lit* (*conc-trail* *st*) (*lit-of* *L*) ⇒

state *st* = (*M*, *S'*) ⇒

state (*cons-conc-trail* *L* *st*) = (*mmset-of-mlit* *L* # *M*, *S'*) **and**

tl-conc-trail:

∧ *S'*. *state* *st* = (*M*, *S'*) ⇒ *state* (*tl-conc-trail* *st*) = (*tl* *M*, *S'*) **and**

remove-cls:

∧ *S'*. *state* *st* = (*M*, *N*, *U*, *S'*) ⇒

state (*remove-cls* *C* *st*) =

(*M*, *removeAll-mset* (*mset-cls* *C*) *N*, *removeAll-mset* (*mset-cls* *C*) *U*, *S'*) **and**

add-conc-confl-to-learned-cls:

no-dup (*conc-trail* *st*) ⇒ *state* *st* = (*M*, *N*, *U*, *k*, *Some* *F*) ⇒

state (*add-conc-confl-to-learned-cls st*) =
 (*M*, *N*, {#*F*#} + *U*, *k*, *None*) **and**

update-conc-backtrack-lvl:

$\bigwedge S'. \text{state } st = (M, N, U, k, S') \implies$
state (*update-conc-backtrack-lvl k' st*) = (*M*, *N*, *U*, *k'*, *S'*) **and**

mark-conflicting:

state st = (*M*, *N*, *U*, *k*, *None*) \implies
state (*mark-conflicting E st*) = (*M*, *N*, *U*, *k*, *Some* (*mset-ccls E*)) **and**

conc-conflicting-mark-conflicting[simp]:

raw-conc-conflicting (*mark-conflicting E st*) = *Some E* **and**

resolve-conflicting:

state st = (*M*, *N*, *U*, *k*, *Some F*) $\implies -L' \in \# F \implies L' \in \# \text{mset-cls } D \implies$
state (*resolve-conflicting L' D st*) =
 (*M*, *N*, *U*, *k*, *Some* (*cdcl_W-mset.resolve-cls L' F* (*mset-cls D*))) **and**

conc-init-state:

state (*conc-init-state Ns*) = (\square , *mset-cls Ns*, {#}, 0, *None*) **and**

— Properties about restarting *restart-state*:

conc-trail-restart-state[simp]: *conc-trail* (*restart-state S*) = \square **and**

conc-init-cls-restart-state[simp]: *conc-init-cls* (*restart-state S*) = *conc-init-cls S* **and**

conc-learned-cls-restart-state[intro]:

conc-learned-cls (*restart-state S*) $\subseteq \#$ *conc-learned-cls S* **and**

conc-backtrack-lvl-restart-state[simp]: *conc-backtrack-lvl* (*restart-state S*) = 0 **and**

conc-conflicting-restart-state[simp]: *conc-conflicting* (*restart-state S*) = *None* **and**

— Properties about *reduce-conc-trail-to*:

reduce-conc-trail-to[simp]:

$\bigwedge S'. \text{conc-trail } st = M2 @ M1 \implies \text{state } st = (M, S') \implies$
state (*reduce-conc-trail-to M1 st*) = (*M1*, *S'*) **and**

learned-clauses:

conc-learned-cls S $\subseteq \#$ *conc-clauses S*

begin

lemma

— Properties about the trail *conc-trail*:

conc-trail-cons-conc-trail[simp]:

undefined-lit (*conc-trail st*) (*lit-of L*) \implies

conc-trail (*cons-conc-trail L st*) = *mmset-of-mlit L* $\#$ *conc-trail st* **and**

conc-trail-tl-conc-trail[simp]:

conc-trail (*tl-conc-trail st*) = *tl* (*conc-trail st*) **and**

conc-trail-add-conc-confl-to-learned-cls[simp]:

no-dup (*conc-trail st*) $\implies \text{conc-conflicting } st \neq \text{None} \implies$

conc-trail (*add-conc-confl-to-learned-cls st*) = *conc-trail st* **and**

conc-trail-remove-cls[simp]:

conc-trail (*remove-cls C st*) = *conc-trail st* **and**

conc-trail-update-conc-backtrack-lvl[simp]:

conc-trail (*update-conc-backtrack-lvl k st*) = *conc-trail st* **and**

conc-trail-mark-conflicting[simp]:

raw-conc-conflicting st = *None* $\implies \text{conc-trail} (\text{mark-conflicting } E \text{ st}) = \text{conc-trail st}$ **and**

conc-trail-resolve-conflicting[simp]:

$\text{conc-conflicting } st = \text{Some } F \implies -L' \in \# F \implies L' \in \# \text{ mset-cls } D \implies$
 $\text{conc-trail } (\text{resolve-conflicting } L' D st) = \text{conc-trail } st \text{ and}$

— Properties about the initial clauses *conc-init-clss*:

$\text{conc-init-clss-cons-conc-trail}[simp]:$
 $\text{undefined-lit } (\text{conc-trail } st) (\text{lit-of } L) \implies$
 $\text{conc-init-clss } (\text{cons-conc-trail } L st) = \text{conc-init-clss } st$
and

— Properties about the learned clauses *conc-learned-clss*:

$\text{conc-learned-clss-cons-conc-trail}[simp]:$
 $\text{undefined-lit } (\text{conc-trail } st) (\text{lit-of } L) \implies$
 $\text{conc-learned-clss } (\text{cons-conc-trail } L st) = \text{conc-learned-clss } st \text{ and}$
 $\text{conc-learned-clss-tl-conc-trail}[simp]:$
 $\text{conc-learned-clss } (\text{tl-conc-trail } st) = \text{conc-learned-clss } st \text{ and}$
 $\text{conc-learned-clss-add-conc-conflict-to-learned-cls}[simp]:$
 $\text{no-dup } (\text{conc-trail } st) \implies \text{conc-conflicting } st = \text{Some } C' \implies$
 $\text{conc-learned-clss } (\text{add-conc-conflict-to-learned-cls } st) = \{\#C'\#\} + \text{conc-learned-clss } st \text{ and}$
 $\text{conc-learned-clss-remove-cls}[simp]:$
 $\text{conc-learned-clss } (\text{remove-cls } C st) = \text{removeAll-mset } (\text{mset-cls } C) (\text{conc-learned-clss } st) \text{ and}$
 $\text{conc-learned-clss-update-conc-backtrack-lvl}[simp]:$
 $\text{conc-learned-clss } (\text{update-conc-backtrack-lvl } k st) = \text{conc-learned-clss } st \text{ and}$
 $\text{conc-learned-clss-mark-conflicting}[simp]:$
 $\text{raw-conc-conflicting } st = \text{None} \implies$
 $\text{conc-learned-clss } (\text{mark-conflicting } E st) = \text{conc-learned-clss } st \text{ and}$
 $\text{conc-learned-clss-clss-resolve-conflicting}[simp]:$
 $\text{conc-conflicting } st = \text{Some } F \implies -L' \in \# F \implies L' \in \# \text{ mset-cls } D \implies$
 $\text{conc-learned-clss } (\text{resolve-conflicting } L' D st) = \text{conc-learned-clss } st \text{ and}$

— Properties about the backtracking level *conc-backtrack-lvl*:

$\text{conc-backtrack-lvl-cons-conc-trail}[simp]:$
 $\text{undefined-lit } (\text{conc-trail } st) (\text{lit-of } L) \implies$
 $\text{conc-backtrack-lvl } (\text{cons-conc-trail } L st) = \text{conc-backtrack-lvl } st \text{ and}$
 $\text{conc-backtrack-lvl-tl-conc-trail}[simp]:$
 $\text{conc-backtrack-lvl } (\text{tl-conc-trail } st) = \text{conc-backtrack-lvl } st \text{ and}$
 $\text{conc-backtrack-lvl-add-conc-conflict-to-learned-cls}[simp]:$
 $\text{no-dup } (\text{conc-trail } st) \implies \text{conc-conflicting } st \neq \text{None} \implies$
 $\text{conc-backtrack-lvl } (\text{add-conc-conflict-to-learned-cls } st) = \text{conc-backtrack-lvl } st \text{ and}$
 $\text{conc-backtrack-lvl-remove-cls}[simp]:$
 $\text{conc-backtrack-lvl } (\text{remove-cls } C st) = \text{conc-backtrack-lvl } st \text{ and}$
 $\text{conc-backtrack-lvl-update-conc-backtrack-lvl}[simp]:$
 $\text{conc-backtrack-lvl } (\text{update-conc-backtrack-lvl } k st) = k \text{ and}$
 $\text{conc-backtrack-lvl-mark-conflicting}[simp]:$
 $\text{raw-conc-conflicting } st = \text{None} \implies$
 $\text{conc-backtrack-lvl } (\text{mark-conflicting } E st) = \text{conc-backtrack-lvl } st \text{ and}$
 $\text{conc-backtrack-lvl-clss-clss-resolve-conflicting}[simp]:$
 $\text{conc-conflicting } st = \text{Some } F \implies -L' \in \# F \implies L' \in \# \text{ mset-cls } D \implies$
 $\text{conc-backtrack-lvl } (\text{resolve-conflicting } L' D st) = \text{conc-backtrack-lvl } st \text{ and}$

— Properties about the conflicting clause *conc-conflicting*:

$\text{conc-conflicting-cons-conc-trail}[simp]:$
 $\text{undefined-lit } (\text{conc-trail } st) (\text{lit-of } L) \implies$
 $\text{conc-conflicting } (\text{cons-conc-trail } L st) = \text{conc-conflicting } st \text{ and}$
 $\text{conc-conflicting-tl-conc-trail}[simp]:$
 $\text{conc-conflicting } (\text{tl-conc-trail } st) = \text{conc-conflicting } st \text{ and}$
 $\text{conc-conflicting-add-conc-conflict-to-learned-cls}[simp]:$

$no_dup (conc_trail\ st) \implies conc_conflicting\ st = Some\ C' \implies$
 $conc_conflicting\ (add_conc_confl_to_learned_cls\ st) = None$
and
 $raw_conc_conflicting_add_conc_confl_to_learned_cls[simp]:$
 $no_dup (conc_trail\ st) \implies conc_conflicting\ st = Some\ C' \implies$
 $raw_conc_conflicting\ (add_conc_confl_to_learned_cls\ st) = None$ **and**
 $conc_conflicting_remove_cls[simp]:$
 $conc_conflicting\ (remove_cls\ C\ st) = conc_conflicting\ st$ **and**
 $conc_conflicting_update_conc_backtrack_lvl[simp]:$
 $conc_conflicting\ (update_conc_backtrack_lvl\ k\ st) = conc_conflicting\ st$ **and**
 $conc_conflicting_clss_clss_resolve_conflicting[simp]:$
 $conc_conflicting\ st = Some\ F \implies -L' \in \# F \implies L' \in \# mset_cls\ D \implies$
 $conc_conflicting\ (resolve_conflicting\ L'\ D\ st) =$
 $Some\ (cdcl_W_mset.resolve_cls\ L'\ F\ (mset_cls\ D))$ **and**

— Properties about the initial state *conc-init-state*:

$conc_init_state_conc_trail[simp]: conc_trail\ (conc_init_state\ Ns) = []$ **and**
 $conc_init_state_clss[simp]: conc_init_clss\ (conc_init_state\ Ns) = mset_clss\ Ns$ **and**
 $conc_init_state_conc_learned_clss[simp]: conc_learned_clss\ (conc_init_state\ Ns) = \{\#\}$ **and**
 $conc_init_state_conc_backtrack_lvl[simp]: conc_backtrack_lvl\ (conc_init_state\ Ns) = 0$ **and**
 $conc_init_state_conc_conflicting[simp]: conc_conflicting\ (conc_init_state\ Ns) = None$ **and**

— Properties about *reduce-conc-trail-to*:

$trail_reduce_conc_trail_to[simp]:$
 $conc_trail\ st = M2\ @\ M1 \implies conc_trail\ (reduce_conc_trail_to\ M1\ st) = M1$ **and**
 $conc_learned_clss_reduce_conc_trail_to[simp]:$
 $conc_trail\ st = M2\ @\ M1 \implies$
 $conc_learned_clss\ (reduce_conc_trail_to\ M1\ st) = conc_learned_clss\ st$ **and**
 $conc_backtrack_lvl_reduce_conc_trail_to[simp]:$
 $conc_trail\ st = M2\ @\ M1 \implies$
 $conc_backtrack_lvl\ (reduce_conc_trail_to\ M1\ st) = conc_backtrack_lvl\ st$ **and**
 $conc_conflicting_reduce_conc_trail_to[simp]:$
 $conc_trail\ st = M2\ @\ M1 \implies$
 $conc_conflicting\ (reduce_conc_trail_to\ M1\ st) = conc_conflicting\ st$
using $cons_conc_trail[of\ st\ L\ conc_trail\ st\ snd\ (state\ st)]\ tl_conc_trail[of\ st]$
 $add_conc_confl_to_learned_cls[of\ st\ conc_trail\ st\ -\ -\ -]$
 $update_conc_backtrack_lvl[of\ st\ -\ -\ -\ -\ k]$
 $mark_conflicting[of\ st\ -\ -\ -\ E]$
 $remove_cls[of\ st\ -\ -\ -\ C]$
 $conc_init_state[of\ Ns]$
 $reduce_conc_trail_to[of\ st]$
 $resolve_conflicting[of\ st\ -\ -\ -\ F\ L'\ D]$
unfolding $state_def\ Product_Type.prod.inject$ **by** *auto*

lemma

$conc_init_clss_tl_conc_trail[simp]:$
 $conc_init_clss\ (tl_conc_trail\ st) = conc_init_clss\ st$ **and**
 $conc_init_clss_add_conc_confl_to_learned_cls[simp]:$
 $no_dup (conc_trail\ st) \implies conc_conflicting\ st \neq None \implies$
 $conc_init_clss\ (add_conc_confl_to_learned_cls\ st) = conc_init_clss\ st$ **and**
 $conc_init_clss_remove_cls[simp]:$
 $conc_init_clss\ (remove_cls\ C\ st) = removeAll_mset\ (mset_cls\ C)\ (conc_init_clss\ st)$ **and**
 $conc_init_clss_update_conc_backtrack_lvl[simp]:$
 $conc_init_clss\ (update_conc_backtrack_lvl\ k\ st) = conc_init_clss\ st$ **and**
 $conc_init_clss_mark_conflicting[simp]:$

```

raw-conc-conflicting st = None  $\implies$ 
  conc-init-clss (mark-conflicting E st) = conc-init-clss st and
conc-init-clss-resolve-conflicting[simp]:
  conc-conflicting st = Some F  $\implies$   $\neg L' \in \# F \implies L' \in \# \text{mset-cls } D \implies$ 
  conc-init-clss (resolve-conflicting L' D st) = conc-init-clss st and
conc-init-clss-reduce-conc-trail-to[simp]:
  conc-trail st = M2 @ M1  $\implies$ 
  conc-init-clss (reduce-conc-trail-to M1 st) = conc-init-clss st
using tl-conc-trail[of st]
add-conc-conflict-to-learned-clss[of st conc-trail st - - -]
update-conc-backtrack-lvl[of st - - - - k]
mark-conflicting[of st - - - - E]
remove-clss[of st - - - - C]
reduce-conc-trail-to[of st M2 M1]
resolve-conflicting[of st - - - - F L' D]
unfolding state-def Product-Type.prod.inject by fast+

```

abbreviation *incr-lvl* :: 'st \Rightarrow 'st **where**

incr-lvl S \equiv update-conc-backtrack-lvl (conc-backtrack-lvl S + 1) S

abbreviation *state-eq* :: 'st \Rightarrow 'st \Rightarrow bool (**infix** \sim 36) **where**

S \sim *T* \equiv state S \sim_m state T

lemma *state-eq-sym*:

S \sim *T* \longleftrightarrow *T* \sim *S*

using cdcl_W-mset.state-eq-sym **by** blast

lemma *state-eq-trans*:

S \sim *T* \implies *T* \sim *U* \implies *S* \sim *U*

using cdcl_W-mset.state-eq-trans **by** blast

lemma *conc-clauses-init-learned*: conc-clauses S = conc-init-clss S + conc-learned-clss S

using learned-clauses[of S] **by** (auto simp: conc-init-clss-def multiset-eq-iff subseq-mset-def)

lemma

shows

state-eq-conc-trail: S \sim T \implies conc-trail S = conc-trail T **and**

state-eq-conc-init-clss: S \sim T \implies conc-init-clss S = conc-init-clss T **and**

state-eq-conc-learned-clss: S \sim T \implies conc-learned-clss S = conc-learned-clss T **and**

state-eq-conc-backtrack-lvl: S \sim T \implies conc-backtrack-lvl S = conc-backtrack-lvl T **and**

state-eq-conc-conflicting: S \sim T \implies conc-conflicting S = conc-conflicting T **and**

state-eq-clauses: S \sim T \implies conc-clauses S = conc-clauses T **and**

state-eq-undefined-lit:

S \sim T \implies undefined-lit (conc-trail S) L = undefined-lit (conc-trail T) L

unfolding state-def cdcl_W-mset.state-eq-def conc-clauses-init-learned

by (auto simp: cdcl_W-mset-state)

We combine all simplification rules about *op* \sim in a single list of theorems. While they are handy as simplification rule as long as we are working on the state, they also cause a *huge* slow-down in all other cases.

lemmas *state-simp* = state-eq-conc-trail state-eq-conc-init-clss state-eq-conc-learned-clss

state-eq-conc-backtrack-lvl state-eq-conc-conflicting state-eq-clauses state-eq-undefined-lit

lemma *atms-of-ms-conc-learned-clss-restart-state-in-atms-of-ms-conc-learned-clssI*[intro]:

$x \in \text{atms-of-mm } (\text{conc-learned-clss } (\text{restart-state } S)) \implies x \in \text{atms-of-mm } (\text{conc-learned-clss } S)$
by (*meson atms-of-ms-mono conc-learned-clss-restart-state set-mset-mono subsetCE*)

lemma *clauses-reduce-conc-trail-to*[simp]:

conc-trail $S = M2 @ M1 \implies \text{conc-clauses } (\text{reduce-conc-trail-to } M1 S) = \text{conc-clauses } S$
unfolding *conc-clauses-init-learned* **by** *auto*

lemma *in-get-all-ann-decomposition-conc-trail-update-conc-trail*[simp]:

assumes $H: (L \# M1, M2) \in \text{set } (\text{get-all-ann-decomposition } (\text{conc-trail } S))$
shows *conc-trail* $(\text{reduce-conc-trail-to } M1 S) = M1$
using *assms* **by** *auto*

lemma *raw-conc-conflicting-cons-conc-trail*[simp]:

assumes *undefined-lit* $(\text{conc-trail } S) (\text{lit-of } L)$
shows
raw-conc-conflicting $(\text{cons-conc-trail } L S) = \text{None} \longleftrightarrow \text{raw-conc-conflicting } S = \text{None}$
using *assms conc-conflicting-cons-conc-trail*[of $S L$] *map-option-is-None* **by** *fastforce+*

lemma *raw-conc-conflicting-update-backtrack-lvl*[simp]:

raw-conc-conflicting $(\text{update-conc-backtrack-lvl } k S) = \text{None} \longleftrightarrow \text{raw-conc-conflicting } S = \text{None}$
using *map-option-is-None conc-conflicting-update-conc-backtrack-lvl*[of $k S$] **by** *fastforce+*

end — end of *state_W* locale

7.2.4 CDCL Rules

locale *abs-conflict-driven-clause-learning_W* =

abs-state_W

— functions for clauses:

mset-cls

mset-clss in-clss insert-clss

— functions for the conflicting clause:

mset-ccls

— conversion

ccls-of-cls cls-of-ccls

— functions for the state:

— access functions:

conc-trail hd-raw-conc-trail raw-clauses conc-backtrack-lvl

raw-conc-conflicting conc-learned-clss

— changing state:

cons-conc-trail tl-conc-trail add-conc-conflict-to-learned-cls remove-cls update-conc-backtrack-lvl

mark-conflicting reduce-conc-trail-to resolve-conflicting

— get state:

conc-init-state

restart-state

for

mset-cls :: $'cls \Rightarrow 'v \text{ clause}$ **and**

mset-clss :: $'clss \Rightarrow 'v \text{ clauses}$ **and**

in-clss :: $'cls \Rightarrow 'clss \Rightarrow \text{bool}$ **and**

insert-clss :: $'cls \Rightarrow 'clss \Rightarrow 'clss$ **and**

mset-clls :: 'ccls \Rightarrow 'v clause **and**

ccls-of-cl :: 'cls \Rightarrow 'ccls **and**

cls-of-clls :: 'ccls \Rightarrow 'cls **and**

conc-trail :: 'st \Rightarrow ('v, 'v clause) ann-lits **and**

hd-raw-conc-trail :: 'st \Rightarrow ('v, 'cls) ann-lit **and**

raw-clauses :: 'st \Rightarrow 'clss **and**

conc-backtrack-lvl :: 'st \Rightarrow nat **and**

raw-conc-conflicting :: 'st \Rightarrow 'ccls option **and**

conc-learned-clss :: 'st \Rightarrow 'v clauses **and**

cons-conc-trail :: ('v, 'cls) ann-lit \Rightarrow 'st \Rightarrow 'st **and**

tl-conc-trail :: 'st \Rightarrow 'st **and**

add-conc-conf-to-learned-cl :: 'st \Rightarrow 'st **and**

remove-cl :: 'cls \Rightarrow 'st \Rightarrow 'st **and**

update-conc-backtrack-lvl :: nat \Rightarrow 'st \Rightarrow 'st **and**

mark-conflicting :: 'ccls \Rightarrow 'st \Rightarrow 'st **and**

reduce-conc-trail-to :: ('v, 'v clause) ann-lits \Rightarrow 'st \Rightarrow 'st **and**

resolve-conflicting :: 'v literal \Rightarrow 'cls \Rightarrow 'st \Rightarrow 'st **and**

conc-init-state :: 'clss \Rightarrow 'st **and**

restart-state :: 'st \Rightarrow 'st

begin

lemma *clauses-state-conc-clauses[simp]*: $\text{cdcl}_W\text{-mset.clauses (state } S) = \text{conc-clauses } S$
apply (cases state *S*)

unfolding *cdcl_W-mset.clauses-def conc-clauses-init-learned*

unfolding *cdcl_W-mset-state state-def*

by *simp*

lemma *conflicting-None-iff-raw-conc-conflicting[simp]*:

conflicting (state S) = None \longleftrightarrow raw-conc-conflicting S = None

unfolding *state-def conflicting-def* **by** *simp*

lemma *trail-state-add-conc-conf-to-learned-cl*:

no-dup (conc-trail S) \implies conc-conflicting S \neq None \implies

trail (state (add-conc-conf-to-learned-cl S)) = trail (state S)

unfolding *trail-def state-def* **by** *simp*

lemma *trail-state-update-backtrack-lvl*:

trail (state (update-conc-backtrack-lvl i S)) = trail (state S)

unfolding *trail-def state-def* **by** *simp*

lemma *trail-state-update-conflicting*:

raw-conc-conflicting S = None \implies trail (state (mark-conflicting i S)) = trail (state S)

unfolding *trail-def state-def* **by** *simp*

lemma *trail-state-conc-trail[simp]*:

trail (state S) = conc-trail S

unfolding *trail-def state-def* **by** *auto*

lemma *init-clss-state-conc-init-clss[simp]*:

init-clss (state S) = conc-init-clss S

unfolding *init-clss-def state-def* **by** *auto*

lemma *learned-clss-state-conc-learned-clss*[simp]:
learned-clss (state *S*) = *conc-learned-clss* *S*
unfolding *learned-clss-def state-def* **by** *auto*

lemma *tl-trail-state-tl-conc-trail*[simp]:
tl-trail (state *S*) = *state* (*tl-conc-trail* *S*)
by (*auto simp: cdcl_W-mset-state state-def simp del: trail-state-conc-trail*
init-clss-state-conc-init-clss
learned-clss-state-conc-learned-clss local.state-simp)

lemma *add-learned-cls-state-add-conc-confl-to-learned-cls*[simp]:
assumes *no-dup* (*conc-trail* *S*) **and** *raw-conc-conflicting* *S* = *Some D*
shows *update-conflicting* *None* (*add-learned-cls* (*mset-ccls* *D*) (state *S*)) =
state (*add-conc-confl-to-learned-cls* *S*)
using *assms* **by** (*auto simp: cdcl_W-mset-state state-def simp del: trail-state-conc-trail*
init-clss-state-conc-init-clss
learned-clss-state-conc-learned-clss local.state-simp)

lemma *state-cons-cons-trail-cons-trail*[simp]:
undefined-lit (*trail* (state *S*)) (*lit-of* *L*) \implies
cons-trail (*mmset-of-mlit* *L*) (state *S*) = *state* (*cons-conc-trail* *L* *S*)
by (*auto simp: cdcl_W-mset-state state-def simp del: trail-state-conc-trail*
init-clss-state-conc-init-clss
learned-clss-state-conc-learned-clss local.state-simp)

lemma *state-cons-cons-trail-cons-trail-propagated*[simp]:
undefined-lit (*trail* (state *S*)) *K* \implies
cons-trail (*Propagated* *K* (*mset-cls* *C*)) (state *S*) = *state* (*cons-conc-trail* (*Propagated* *K* *C*) *S*)
using *state-cons-cons-trail-cons-trail*[of *S* *Propagated* *K* *C*] **by** *simp*

lemma *state-cons-cons-trail-cons-trail-propagated-ccls*[simp]:
undefined-lit (*trail* (state *S*)) *K* \implies
cons-trail (*Propagated* *K* (*mset-ccls* *C*)) (state *S*) =
state (*cons-conc-trail* (*Propagated* *K* (*cls-of-ccls* *C*)) *S*)
using *state-cons-cons-trail-cons-trail*[of *S* *Propagated* *K* (*cls-of-ccls* *C*)] **by** *simp*

lemma *state-cons-cons-trail-cons-trail-decided*[simp]:
undefined-lit (*trail* (state *S*)) *K* \implies
cons-trail (*Decided* *K*) (state *S*) = *state* (*cons-conc-trail* (*Decided* *K*) *S*)
using *state-cons-cons-trail-cons-trail*[of *S* *Decided* *K*] **by** *simp*

lemma *state-mark-conflicting-update-conflicting*[simp]:
assumes *raw-conc-conflicting* *S* = *None*
shows
update-conflicting (*Some* (*mset-ccls* *D*)) (state *S*) = *state* (*mark-conflicting* *D* *S*)
update-conflicting (*Some* (*mset-cls* *D'*)) (state *S*) =
state (*mark-conflicting* ((*ccls-of-cls* *D'*)) *S*)
using *assms* **by** (*auto simp: cdcl_W-mset-state state-def simp del: trail-state-conc-trail*
init-clss-state-conc-init-clss
learned-clss-state-conc-learned-clss local.state-simp)

lemma *update-backtrack-lvl-state*[simp]:
update-backtrack-lvl *i* (state *S*) = *state* (*update-conc-backtrack-lvl* *i* *S*)
by (*auto simp: cdcl_W-mset-state state-def simp del: trail-state-conc-trail*
init-clss-state-conc-init-clss
learned-clss-state-conc-learned-clss local.state-simp)

lemma *conc-conflicting-conflicting*[simp]:
conflicting (state S) = conc-conflicting S
by (auto simp: *cdcl_W-mset-state state-def simp del: trail-state-conc-trail*
init-clss-state-conc-init-clss
learned-clss-state-conc-learned-clss local.state-simp)

lemma *update-conflicting-resolve-state-mark-conflicting*[simp]:
raw-conc-conflicting S = Some D' \implies $\neg L \in \# \text{mset-ccls } D' \implies L \in \# \text{mset-cls } E' \implies$
update-conflicting (Some (remove1-mset (\neg L) (mset-ccls D') $\# \cup$ remove1-mset L (mset-cls E')))
(state (tl-conc-trail S)) =
state (resolve-conflicting L E' (tl-conc-trail S))
by (auto simp: *cdcl_W-mset-state state-def simp del: trail-state-conc-trail*
init-clss-state-conc-init-clss
learned-clss-state-conc-learned-clss local.state-simp)

lemma *add-learned-update-backtrack-update-conflicting*[simp]:
no-dup (conc-trail S) \implies raw-conc-conflicting S = Some D' \implies add-learned-cls (mset-ccls D')
(update-backtrack-lvl i
(update-conflicting None
(state S))) =
state (add-conc-conflict-to-learned-cls (update-conc-backtrack-lvl i S))
by (auto simp: *cdcl_W-mset-state state-def simp del: trail-state-conc-trail*
init-clss-state-conc-init-clss
learned-clss-state-conc-learned-clss local.state-simp)

lemma *conc-backtrack-lvl-backtrack-lvl*[simp]:
backtrack-lvl (state S) = conc-backtrack-lvl S
unfolding *state-def* **by** (auto simp: *cdcl_W-mset-state*)

lemma *state-state*:
cdcl_W-mset.state (state S) = (trail (state S), init-clss (state S), learned-clss (state S),
backtrack-lvl (state S), conflicting (state S))
by (*simp*)

lemma *state-reduce-conc-trail-to-reduce-conc-trail-to*[simp]:
assumes [*simp*]: *conc-trail S = M2 @ M1*
shows *cdcl_W-mset.reduce-trail-to M1 (state S) = state (reduce-conc-trail-to M1 S) (is ?RS = ?SR)*
proof –
have 1: *trail ?SR = trail ?RS*
apply (*subst state-def*)
apply (*auto simp add: cdcl_W-mset.trail-reduce-trail-to-drop*)
apply (*auto simp: trail-def*)
done

have 2: *init-clss ?SR = init-clss ?RS*
by *simp*

have 3: *learned-clss ?SR = learned-clss ?RS*
by *simp*

have 4: *backtrack-lvl ?SR = backtrack-lvl ?RS*
by *simp*

have 5: *conflicting ?SR = conflicting ?RS*
by *simp*

```

show ?thesis
  using 1 2 3 4 5 apply -
  apply (subst (asm) trail-def, subst (asm) trail-def)
  apply (subst (asm) init-clss-def, subst (asm) init-clss-def)
  apply (subst (asm) learned-clss-def, subst (asm) learned-clss-def)
  apply (subst (asm) backtrack-lvl-def, subst (asm) backtrack-lvl-def)
  apply (subst (asm) conflicting-def, subst (asm) conflicting-def)
  apply (cases state (reduce-conc-trail-to M1 S))
  apply (cases cdclW-mset.reduce-trail-to M1 (state S))
  by simp
qed

```

lemma *state-conc-init-state*: $\text{state} (\text{conc-init-state } N) = \text{init-state} (\text{mset-clss } N)$
by (*auto simp: cdcl_W-mset-state state-def simp del: trail-state-conc-trail*
init-clss-state-conc-init-clss
learned-clss-state-conc-learned-clss local.state-simp)

More robust version of *in-mset-clss-exists-preimage*:

lemma *in-clauses-preimage*:
assumes $b: b \in \# \text{ cdcl}_W\text{-mset.clauses} (\text{state } C)$
shows $\exists b'. b' \in \# \text{ raw-clauses } C \wedge \text{mset-cls } b' = b$
proof -
have $b \in \# \text{ conc-clauses } C$
using b **by** *auto*
from *in-mset-clss-exists-preimage[OF this]* **show** ?thesis .
qed

lemma *state-reduce-conc-trail-to-reduce-conc-trail-to-decomp[simp]*:
assumes $(P \# M1, M2) \in \text{set} (\text{get-all-ann-decomposition} (\text{conc-trail } S))$
shows $\text{cdcl}_W\text{-mset.reduce-trail-to } M1 (\text{state } S) = \text{state} (\text{reduce-conc-trail-to } M1 S)$
using *assms* **by** *auto*

inductive *propagate-abs* :: '*st* \Rightarrow '*st* \Rightarrow bool **for** $S ::$ '*st* **where**
propagate-abs-rule: $\text{conc-conflicting } S = \text{None} \Rightarrow$
 $E \in \# \text{ raw-clauses } S \Rightarrow$
 $L \in \# \text{ mset-cls } E \Rightarrow$
 $\text{conc-trail } S \models_{\text{as}} \text{CNot} (\text{mset-cls } E - \{\#L\# \}) \Rightarrow$
 $\text{undefined-lit} (\text{conc-trail } S) L \Rightarrow$
 $T \sim \text{cons-conc-trail} (\text{Propagated } L E) S \Rightarrow$
propagate-abs $S T$

inductive-cases *propagate-absE*: *propagate-abs* $S T$

lemma *propagate-propagate-abs*:
 $\text{cdcl}_W\text{-mset.propagate} (\text{state } S) (\text{state } T) \longleftrightarrow \text{propagate-abs } S T$ (**is** ?*mset* \longleftrightarrow ?*abs*)

proof
assume ?*abs*
then obtain $E L$ **where**
confl: $\text{conc-conflicting } S = \text{None}$ **and**
 $E: E \in \# \text{ raw-clauses } S$ **and**
 $L: L \in \# \text{ mset-cls } E$ **and**
tr-E: $\text{conc-trail } S \models_{\text{as}} \text{CNot} (\text{mset-cls } E - \{\#L\# \})$ **and**
undef: $\text{undefined-lit} (\text{conc-trail } S) L$ **and**
 $T: T \sim \text{cons-conc-trail} (\text{Propagated } L E) S$
by (*auto elim: propagate-absE*)

```

show ?mset
  apply (rule cdclW-mset.propagate-rule)
    using confl apply auto[]
    using E apply auto[]
    using L apply auto[]
    using tr-E apply auto[]
    using undef apply (auto simp:)[ ]
  using undef T unfolding cdclW-mset-state-eq-eq state-def cons-trail-def by simp
next
assume ?mset
then obtain E L where
  conc-conflicting S = None and
  E !∈ raw-clauses S and
  L ∈# mset-cls E and
  conc-trail S ⊨as CNot (mset-cls E - {#L#}) and
  undefined-lit (conc-trail S) L and
  state T ~m cons-trail (Propagated L (mset-cls E)) (state S)
  by (auto elim!: cdclW-mset.propagateE dest!: in-clauses-preimage
      simp: cdclW-mset.clauses-def)
then show ?abs
  by (auto intro!: propagate-abs-rule)
qed

```

lemma *propagate-compatible-abs:*

```

assumes SS': S ~m state S' and abs: cdclW-mset.propagate S T
obtains U where propagate-abs S' U and T ~m state U
proof -
  obtain E L where
    confl: conflicting S = None and
    E: E ∈# cdclW-mset.clauses S and
    L: L ∈# E and
    tr: trail S ⊨as CNot (E - {#L#}) and
    undef: undefined-lit (trail S) L and
    T: T ~m cons-trail (Propagated L E) S
  using abs by (auto elim!: cdclW-mset.propagateE dest!: in-clauses-preimage
      simp: cdclW-mset.clauses-def)
  then obtain E' where
    E': E' !∈ raw-clauses S' and [simp]: E = mset-cls E'
  by (metis SS' cdclW-mset.state-eq-clauses in-clauses-preimage)
  let ?U = cons-conc-trail (Propagated L E') S'
  have propagate-abs S' ?U
  apply (rule propagate-abs-rule)
    using confl SS' apply simp
    using E' SS' apply simp
    using L apply simp
    using tr SS' apply simp
    using undef SS' apply simp
  using undef SS' by simp
  moreover have T ~m state ?U
  using T SS' undef by (auto simp: cdclW-mset.state-eq-eq)
  ultimately show thesis using that by blast
qed

```

interpretation *propagate-abs: relation-relation-abs cdcl_W-mset.propagate propagate-abs state*
 $\lambda\cdot. \text{True}$

apply *unfold-locales*
apply (*simp add: propagate-propagate-abs*)
using *propagate-compatible-abs* **by** *blast*

inductive *conflict-abs* :: '*st* \Rightarrow '*st* \Rightarrow bool **for** *S* :: '*st* **where**

conflict-abs-rule:

conc-conflicting S = None \implies
D ! \in ! raw-clauses S \implies
conc-trail S \models_{as} CNot (mset-cls D) \implies
T \sim mark-conflicting (ccls-of-cls D) S \implies
conflict-abs S T

inductive-cases *conflict-absE*: *conflict-abs S T*

lemma *conflict-conflict-abs*:

cdcl_W-mset.conflict (state S) (state T) \longleftrightarrow conflict-abs S T (is ?mset \longleftrightarrow ?abs)

proof

assume ?abs

then obtain *D* **where**

confl: conc-conflicting S = None and
D: D ! \in ! raw-clauses S and
tr-D: conc-trail S \models_{as} CNot (mset-cls D) and
T: T \sim mark-conflicting (ccls-of-cls D) S
by (*auto elim!: conflict-absE*)

show ?mset

apply (*rule cdcl_W-mset.conflict-rule*)
using *confl* **apply** *simp*
using *D* **apply** *auto*[]
using *tr-D* **apply** *simp*
using *T confl* **apply** *auto*
done

next

assume ?mset

then obtain *D* **where**

confl: conflicting (state S) = None and
D: D \in # cdcl_W-mset.clauses (state S) and
tr-D: trail (state S) \models_{as} CNot D and
T: state T \sim_m update-conflicting (Some D) (state S)
by (*cases state S*) (*auto elim: cdcl_W-mset.conflictE*)

obtain *D'* **where** *D': D' ! \in ! raw-clauses S and DD'[simp]: D = mset-cls D'*

using *D* **by** (*auto dest!: in-mset-clss-exists-preimage*)[]

show ?abs

apply (*rule conflict-abs-rule*)
using *confl* **apply** *simp*
using *D'* **apply** *simp*
using *tr-D* **apply** *simp*
using *T confl* **by** *auto*

qed

lemma *conflict-compatible-abs*:

assumes *SS'*: *S \sim_m state S' and conflict: cdcl_W-mset.conflict S T*

obtains *U* **where** *conflict-abs S' U and T \sim_m state U*

proof –

obtain *D* **where**

confl: conflicting S = None and
D: D \in # cdcl_W-mset.clauses S and

tr-D: trail $S \models_{as} CNot\ D$ **and**
 T : $T \sim_m update-conflicting\ (Some\ D)\ S$
using *conflict* **by** (*auto elim*: *cdcl_W-mset.conflictE*)
obtain D' **where** D' : $D' \notin raw-clauses\ S'$ **and** $DD'[simp]$: $D = mset-cls\ D'$
using $D\ SS'$ **by** (*auto dest*!: *in-mset-clss-exists-preimage*)[]
let $?U = mark-conflicting\ (ccls-of-cls\ D')\ S'$
have *conflict-abs* $S'\ ?U$
apply (*rule conflict-abs-rule*)
using *confl* SS' **apply** *simp*
using $D'\ SS'$ **apply** *simp*
using *tr-D* SS' **apply** *simp*
using T **by** *auto*
moreover **have** $T \sim_m state\ ?U$
using $T\ SS'$ *confl* **by** (*auto simp*: *cdcl_W-mset-state-eq-eq*)
ultimately **show** *thesis* **using** *that*[*of* $?U$] **by** *fast*
qed

interpretation *conflict-abs*: *relation-relation-abs cdcl_W-mset.conflict conflict-abs state*
 $\lambda\cdot. True$
apply *unfold-locales*
apply (*simp add*: *conflict-conflict-abs*)
using *conflict-compatible-abs* **by** *metis*

inductive *backtrack-abs* :: '*st* \Rightarrow '*st* \Rightarrow bool **for** $S :: '$ *st* **where**
backtrack-abs-rule:

$raw-conc-conflicting\ S = Some\ D \implies$
 $L \in \# mset-ccls\ D \implies$
 $(Decided\ K \# M1, M2) \in set\ (get-all-ann-decomposition\ (conc-trail\ S)) \implies$
 $get-level\ (conc-trail\ S)\ L = conc-backtrack-lvl\ S \implies$
 $get-level\ (conc-trail\ S)\ L = get-maximum-level\ (conc-trail\ S)\ (mset-ccls\ D) \implies$
 $get-maximum-level\ (conc-trail\ S)\ (mset-ccls\ D - \{\#L\# \}) \equiv i \implies$
 $get-level\ (conc-trail\ S)\ K = i + 1 \implies$
 $T \sim cons-conc-trail\ (Propagated\ L\ (cls-of-ccls\ D))$
 $(reduce-conc-trail-to\ M1$
 $(add-conc-confl-to-learned-cls$
 $(update-conc-backtrack-lvl\ i\ S))) \implies$
backtrack-abs $S\ T$

inductive-cases *backtrack-absE*: *backtrack-abs* $S\ T$

lemma *backtrack-backtrack-abs*:

assumes *inv*: *cdcl_W-mset.cdcl_W-all-struct-inv* (*state* S)
shows *cdcl_W-mset.backtrack* (*state* S) (*state* T) \longleftrightarrow *backtrack-abs* $S\ T$ (**is** $?conc \longleftrightarrow ?abs$)

proof

assume $?abs$

then obtain $D\ L\ K\ M1\ M2\ i$ **where**

D : *raw-conc-conflicting* $S = Some\ D$ **and**

L : $L \in \# mset-ccls\ D$ **and**

decomp: $(Decided\ K \# M1, M2) \in set\ (get-all-ann-decomposition\ (conc-trail\ S))$ **and**

lev-L: $get-level\ (conc-trail\ S)\ L = conc-backtrack-lvl\ S$ **and**

lev-Max: $get-level\ (conc-trail\ S)\ L = get-maximum-level\ (conc-trail\ S)\ (mset-ccls\ D)$ **and**

i : $get-maximum-level\ (conc-trail\ S)\ (mset-ccls\ D - \{\#L\# \}) \equiv i$ **and**

lev-K: $get-level\ (conc-trail\ S)\ K = i + 1$ **and**

T : $T \sim cons-conc-trail\ (Propagated\ L\ (cls-of-ccls\ D))$

$(reduce-conc-trail-to\ M1$

$(add-conc-confl-to-learned-cls$

```

      (update-conc-backtrack-lvl i S)))
  by (auto elim!: backtrack-absE)
have n-d: no-dup (trail (state S))
  using lev-L inv unfolding cdclW-mset.cdclW-all-struct-inv-def cdclW-mset.cdclW-M-level-inv-def
  by simp
have atm-of L  $\notin$  atm-of ' lits-of-l M1
  apply (rule cdclW-mset.backtrack-lit-skipped[of - state S])
    using lev-L inv unfolding cdclW-mset.cdclW-all-struct-inv-def cdclW-mset.cdclW-M-level-inv-def
    apply simp
    using decomp apply simp
  using lev-L inv unfolding cdclW-mset.cdclW-all-struct-inv-def cdclW-mset.cdclW-M-level-inv-def
  apply simp
  using lev-L inv unfolding cdclW-mset.cdclW-all-struct-inv-def cdclW-mset.cdclW-M-level-inv-def
  apply simp
using lev-K apply simp
done
then have undef: undefined-lit M1 L
  by (auto simp add: defined-lit-map lits-of-def)
obtain c where tr: conc-trail S = c @ M2 @ Decided K # M1
  using decomp by auto
show ?conc
  apply (rule cdclW-mset.backtrack-rule)
    using D apply simp
    using L apply simp
    using decomp apply simp
    using lev-L apply simp
    using lev-Max apply simp
    using i apply simp
    using lev-K apply simp
  using T undef n-d tr D unfolding cdclW-mset.state-eq-def
  by auto
next
assume ?conc
then obtain L D K M1 M2 i where
  confl: conflicting (state S) = Some D and
  L: L  $\in$  # D and
  decomp: (Decided K # M1, M2)  $\in$  set (get-all-ann-decomposition (trail (state S))) and
  lev-L: get-level (trail (state S)) L = backtrack-lvl (state S) and
  lev-max: get-level (trail (state S)) L = get-maximum-level (trail (state S)) (D) and
  i: get-maximum-level (trail (state S)) (D - {#L#})  $\equiv$  i and
  lev-K: get-level (trail (state S)) K = i + 1 and
  T: state T  $\sim_m$  cons-trail (Propagated L (D))
    (cdclW-mset.reduce-trail-to M1
      (add-learned-cls D
        (update-backtrack-lvl i
          (update-conflicting None (state S))))))
  by (auto elim: cdclW-mset.backtrackE)
obtain D' where
  confl': raw-conc-conflicting S = Some D' and D[simp]: D = mset-ccls D'
  using confl by auto
have n-d: no-dup (trail (state S))
  using lev-L inv unfolding cdclW-mset.cdclW-all-struct-inv-def cdclW-mset.cdclW-M-level-inv-def
  by simp
have atm-of L  $\notin$  atm-of ' lits-of-l M1
  apply (rule cdclW-mset.backtrack-lit-skipped[of - state S])
    using lev-L inv unfolding cdclW-mset.cdclW-all-struct-inv-def cdclW-mset.cdclW-M-level-inv-def

```

```

    apply simp
    using decomp apply simp
    using lev-L inv unfolding cdclW-mset.cdclW-all-struct-inv-def cdclW-mset.cdclW-M-level-inv-def
    apply simp
    using lev-L inv unfolding cdclW-mset.cdclW-all-struct-inv-def cdclW-mset.cdclW-M-level-inv-def
    apply simp
    using lev-K apply simp
  done
then have undef: undefined-lit M1 L
  by (auto simp add: defined-lit-map lits-of-def)
show ?abs
  apply (rule backtrack-abs-rule)
    using confl' apply simp
    using L apply simp
    using decomp apply simp
    using lev-L apply simp
    using lev-max apply simp
    using i apply simp
    using lev-K apply simp
  using T undef n-d decomp confl' by auto
qed

```

lemma *backtrack-exists-backtrack-abs-step*:

assumes *bt*: cdcl_W-mset.backtrack *S T* **and** *inv*: cdcl_W-mset.cdcl_W-all-struct-inv *S* **and**
SS': *S* \sim_m state *S'*

obtains *U* **where** backtrack-abs *S' U* **and** *T* \sim_m state *U*

proof –

from *bt* **obtain** *L D K M1 M2 i* **where**

confl: conflicting *S* = Some *D* **and**

L: *L* $\in \#$ *D* **and**

decomp: (Decided *K* $\#$ *M1*, *M2*) \in set (get-all-ann-decomposition (trail *S*)) **and**

lev-L: get-level (trail *S*) *L* = backtrack-lvl *S* **and**

lev-max: get-level (trail *S*) *L* = get-maximum-level (trail *S*) (*D*) **and**

i: get-maximum-level (trail *S*) (*D* - { $\#L\#$ }) $\equiv i$ **and**

lev-K: get-level (trail *S*) *K* = *i* + 1 **and**

T: *T* \sim_m cons-trail (Propagated *L* (*D*))

(cdcl_W-mset.reduce-trail-to *M1*

(add-learned-cls *D*

(update-backtrack-lvl *i*

(update-conflicting None *S*))))

by (auto elim: cdcl_W-mset.backtrackE)

obtain *D'* **where**

confl': raw-conc-conflicting *S'* = Some *D'* **and** *D*[simp]: *D* = mset-ccls *D'*

using confl *SS'* **by** auto

have *n-d*: no-dup (trail (state *S'*))

using lev-L inv *SS'* **unfolding** cdcl_W-mset.cdcl_W-all-struct-inv-def cdcl_W-mset.cdcl_W-M-level-inv-def
by simp

have atm-of *L* \notin atm-of ' lits-of-l *M1*

apply (rule cdcl_W-mset.backtrack-lit-skipped[of - state *S'*])

using lev-L inv *SS'* **unfolding** cdcl_W-mset.cdcl_W-all-struct-inv-def cdcl_W-mset.cdcl_W-M-level-inv-def
apply simp

using decomp *SS'* **apply** simp

using lev-L inv *SS'* **unfolding** cdcl_W-mset.cdcl_W-all-struct-inv-def cdcl_W-mset.cdcl_W-M-level-inv-def
apply simp

using lev-L inv *SS'* **unfolding** cdcl_W-mset.cdcl_W-all-struct-inv-def cdcl_W-mset.cdcl_W-M-level-inv-def
apply simp

```

using lev-K SS' apply simp
done
then have undef: undefined-lit M1 L
  by (auto simp add: defined-lit-map lits-of-def)

let ?U = cons-conc-trail (Propagated L (cls-of-ccls D'))
  (reduce-conc-trail-to M1
    (add-conc-confl-to-learned-cls
      (update-conc-backtrack-lvl i S')))
have backtrack-abs S' ?U
  apply (rule backtrack-abs-rule)
  using confl' apply simp
  using L apply simp
  using decomp SS' apply simp
  using lev-L SS' apply simp
  using lev-max SS' apply simp
  using i SS' apply simp
  using lev-K SS' apply simp
  using T undef n-d decomp by auto
moreover have T ~m state ?U
  using undef decomp T n-d SS'[unfolded cdclW-mset-state-eq-eq] confl' by auto
ultimately show thesis using that[of ?U] by fast
qed

```

interpretation *backtrack-abs: relation-relation-abs cdcl_W-mset.backtrack backtrack-abs state*
cdcl_W-mset.cdcl_W-all-struct-inv
apply *unfold-locales*
apply (*simp add: backtrack-backtrack-abs*)
using *backtrack-exists-backtrack-abs-step* **apply** *metis*
using *cdcl_W-mset.backtrack cdcl_W-mset.bj cdcl_W-mset.cdcl_W-all-struct-inv-inv* **by** *blast*

inductive *decide-abs :: 'st ⇒ 'st ⇒ bool* **for** *S :: 'st* **where**

decide-abs-rule:

conc-conflicting S = None ⇒
undefined-lit (conc-trail S) L ⇒
atm-of L ∈ atms-of-mm (conc-init-clss S) ⇒
T ~ cons-conc-trail (Decided L) (incr-lvl S) ⇒
decide-abs S T

inductive-cases *decide-absE: decide-abs S T*

lemma *decide-decide-abs:*

cdcl_W-mset.decide (state S) (state T) ⟷ decide-abs S T
by (*auto elim!: cdcl_W-mset.decideE decide-absE intro!: cdcl_W-mset.decide-rule decide-abs-rule*)

interpretation *decide-abs: relation-relation-abs cdcl_W-mset.decide decide-abs state*

λ-. True

apply *unfold-locales*

apply (*simp add: decide-decide-abs*)

apply (*metis (full-types) cdcl_W-mset.decide.cases cdcl_W-mset-state-eq-eq*
conc-trail-update-conc-backtrack-lvl decide-decide-abs

state-cons-cons-trail-cons-trail-decided trail-state-conc-trail update-backtrack-lvl-state)

using *cdcl_W-mset.cdcl_W-all-struct-inv-inv cdcl_W-mset.decide cdcl_W-mset.other* **by** *blast*

inductive *skip-abs :: 'st ⇒ 'st ⇒ bool* **for** *S :: 'st* **where**

skip-abs-rule:

$\text{conc-trail } S = \text{Propagated } L \ C' \ \# \ M \implies$
 $\text{raw-conc-conflicting } S = \text{Some } E \implies$
 $-L \notin \# \ \text{mset-ccls } E \implies$
 $\text{mset-ccls } E \neq \{\#\} \implies$
 $T \sim \text{tl-conc-trail } S \implies$
 $\text{skip-abs } S \ T$

inductive-cases skip-absE : $\text{skip-abs } S \ T$

lemma skip-skip-abs :

$\text{cdcl}_W\text{-mset.skip } (\text{state } S) \ (\text{state } T) \longleftrightarrow \text{skip-abs } S \ T \ (\text{is } ?\text{conc} \longleftrightarrow ?\text{abs})$

proof

assume $?abs$

then show $?conc$

by (auto elim! : skip-absE intro! : $\text{cdcl}_W\text{-mset.skip-rule}$)

next

assume $?conc$

then obtain $L \ C' \ E \ M$ **where**

tr : $\text{trail } (\text{state } S) = \text{Propagated } L \ C' \ \# \ M$ **and**

confl : $\text{conflicting } (\text{state } S) = \text{Some } E$ **and**

L : $-L \notin \# \ E$ **and**

E : $E \neq \{\#\}$ **and**

T : $\text{state } T \sim_m \text{tl-trail } (\text{state } S)$

by (auto elim : $\text{cdcl}_W\text{-mset.skipE}$)

obtain E' **where**

confl' : $\text{raw-conc-conflicting } S = \text{Some } E'$ **and** $[\text{simp}]$: $E = \text{mset-ccls } E'$

using confl **by** auto

show $?abs$

apply ($\text{rule skip-abs-rule}$)

using tr **apply** simp

using confl' **apply** simp

using L **apply** simp

using E **apply** simp

using T **by** simp

qed

lemma $\text{skip-exists-skip-abs}$:

assumes skip : $\text{cdcl}_W\text{-mset.skip } S \ T$ **and** SS' : $S \sim_m \text{state } S'$

obtains U **where** $\text{skip-abs } S' \ U$ **and** $T \sim_m \text{state } U$

proof –

obtain $L \ C' \ E \ M$ **where**

tr : $\text{trail } S = \text{Propagated } L \ C' \ \# \ M$ **and**

confl : $\text{conflicting } S = \text{Some } E$ **and**

L : $-L \notin \# \ E$ **and**

E : $E \neq \{\#\}$ **and**

T : $T \sim_m \text{tl-trail } S$

using skip **by** (auto elim : $\text{cdcl}_W\text{-mset.skipE}$)

obtain E' **where**

confl' : $\text{raw-conc-conflicting } S' = \text{Some } E'$ **and** $[\text{simp}]$: $E = \text{mset-ccls } E'$

using confl SS' **by** auto

have $\text{skip-abs } S' \ (\text{tl-conc-trail } S')$

apply ($\text{rule skip-abs-rule}$)

using tr SS' **apply** simp

using confl' SS' **apply** simp

using L SS' **apply** simp

using E **apply** simp

```

    using T by simp
  then show ?thesis
    using that[of tl-conc-trail S] T SS'[unfolded cdclW-mset-state-eq-eq ] by auto
qed

```

```

interpretation skip-abs: relation-relation-abs cdclW-mset.skip skip-abs state
λ-. True
apply unfold-locales
  apply (simp add: skip-skip-abs)
  using skip-exists-skip-abs applymetis
using cdclW-mset.cdclW-all-struct-inv-inv cdclW-mset.skip cdclW-mset.other by blast

```

```

inductive resolve-abs :: 'st ⇒ 'st ⇒ bool for S :: 'st where
  resolve-abs-rule: conc-trail S ≠ [] ⇒
    hd-raw-conc-trail S = Propagated L E ⇒
    L ∈# mset-cls E ⇒
    raw-conc-conflicting S = Some D' ⇒
    -L ∈# mset-ccls D' ⇒
    get-maximum-level (conc-trail S) (remove1-mset (-L) (mset-ccls D')) = conc-backtrack-lvl S ⇒
    T ~ resolve-conflicting L E (tl-conc-trail S) ⇒
    resolve-abs S T

```

```

inductive-cases resolve-absE: resolve-abs S T

```

```

lemma resolve-resolve-abs:

```

```

  cdclW-mset.resolve (state S) (state T) ⟷ resolve-abs S T (is ?conc ⟷ ?abs)

```

```

proof

```

```

  assume ?conc

```

```

  then obtain L E D where

```

```

    tr: trail (state S) ≠ [] and

```

```

    hd: cdclW-mset.hd-trail (state S) = Propagated L E and

```

```

    LE: L ∈# E and

```

```

    confl: conflicting (state S) = Some D and

```

```

    LD: -L ∈# D and

```

```

    lvl-max: get-maximum-level (trail (state S)) ((remove1-mset (-L) D)) = backtrack-lvl (state S) and

```

```

    T: state T ~m update-conflicting (Some (cdclW-mset.resolve-cls L D E)) (tl-trail (state S))

```

```

  by (auto elim!: cdclW-mset.resolveE)

```

```

obtain E' where

```

```

    hd': hd-raw-conc-trail S = Propagated L E' and

```

```

    [simp]: E = mset-cls E'

```

```

  apply (cases hd-raw-conc-trail S)

```

```

  using hd-raw-conc-trail[of S] tr hd by simp-all

```

```

obtain D' where

```

```

    confl': raw-conc-conflicting S = Some D' and

```

```

    [simp]: D = mset-ccls D'

```

```

  using confl by auto

```

```

show ?abs

```

```

  apply (rule resolve-abs-rule)

```

```

    using tr apply simp

```

```

    using hd' apply simp

```

```

    using LE apply simp

```

```

    using confl' apply simp

```

```

    using LD apply simp

```

```

    using lvl-max apply simp

```

```

    using T confl' LE LD by simp

```

```

next

```

assume $?abs$
then show $?conc$
 using $hd\text{-}raw\text{-}conc\text{-}trail[of\ S]$ **by** $(auto\ elim!\!: resolve\text{-}absE\ intro!\!: cdcl_W\text{-}mset.resolve\text{-}rule)$
qed

lemma *resolve-exists-resolve-abs*:

assumes
 $res: cdcl_W\text{-}mset.resolve\ S\ T$ **and**
 $SS': S \sim_m state\ S'$
obtains U **where** $resolve\text{-}abs\ S'\ U$ **and** $T \sim_m state\ U$
proof –
obtain $L\ E\ D$ **where**
 $tr: trail\ S \neq []$ **and**
 $hd: cdcl_W\text{-}mset.hd\text{-}trail\ S = Propagated\ L\ E$ **and**
 $LE: L \in\# E$ **and**
 $confl: conflicting\ S = Some\ D$ **and**
 $LD: -L \in\# D$ **and**
 $lvl\text{-}max: get\text{-}maximum\text{-}level\ (trail\ S)\ ((remove1\text{-}mset\ (-L)\ D)) = backtrack\text{-}lvl\ S$ **and**
 $T: T \sim_m update\text{-}conflicting\ (Some\ (cdcl_W\text{-}mset.resolve\text{-}cls\ L\ D\ E))\ (tl\text{-}trail\ S)$
using res
by $(auto\ elim!\!: cdcl_W\text{-}mset.resolveE)$
obtain E' **where**
 $hd': hd\text{-}raw\text{-}conc\text{-}trail\ S' = Propagated\ L\ E'$ **and**
 $[simp]: E = mset\text{-}cls\ E'$
apply $(cases\ hd\text{-}raw\text{-}conc\text{-}trail\ S')$
using $hd\text{-}raw\text{-}conc\text{-}trail[of\ S']\ tr\ hd\ SS'$ **by** $simp\text{-}all$
obtain D' **where**
 $confl': raw\text{-}conc\text{-}conflicting\ S' = Some\ D'$ **and**
 $[simp]: D = mset\text{-}ccls\ D'$
using $confl\ SS'$ **by** $auto$
let $?U = resolve\text{-}conflicting\ L\ E'\ (tl\text{-}conc\text{-}trail\ S')$
have $resolve\text{-}abs\ S'\ ?U$
apply $(rule\ resolve\text{-}abs\text{-}rule)$
using $tr\ SS'$ **apply** $simp$
using hd' **apply** $simp$
using LE **apply** $simp$
using $confl'$ **apply** $simp$
using LD **apply** $simp$
using $lvl\text{-}max\ SS'$ **apply** $simp$
using T **by** $simp$
moreover have $T \sim_m state\ ?U$
using $T\ SS'\ confl\ LE\ LD$ **unfolding** $cdcl_W\text{-}mset.state\text{-}eq\text{-}def$ **by** $fastforce$
ultimately show $thesis$ **using** $that[of\ ?U]$ **by** $fast$
qed

interpretation *resolve-abs: relation-relation-abs* $cdcl_W\text{-}mset.resolve\ resolve\text{-}abs\ state$

$\lambda\text{-}.$ *True*

apply *unfold-locales*

apply $(simp\ add: resolve\text{-}resolve\text{-}abs)$

using *resolve-exists-resolve-abs* **apply** *metis*

using $cdcl_W\text{-}mset.cdcl_W\text{-}all\text{-}struct\text{-}inv\text{-}inv\ cdcl_W\text{-}mset.resolve\ cdcl_W\text{-}mset.other$ **by** *blast*

inductive *restart* $:: 'st \Rightarrow 'st \Rightarrow bool$ **for** $S :: 'st$ **where**

restart: $conc\text{-}conflicting\ S = None \implies$

$\neg conc\text{-}trail\ S \models_{asm} conc\text{-}clauses\ S \implies$

$T \sim restart\text{-}state\ S \implies$

restart S T

inductive-cases *restartE*: *restart S T*

We add the condition $C \notin \# \text{conc-init-clss } S$, to maintain consistency even without the strategy.

inductive *forget* :: '*st* \Rightarrow '*st* \Rightarrow bool **where**

forget-rule:

conc-conflicting S = None \Rightarrow
C ! \in ! raw-conc-learned-clss S \Rightarrow
 $\neg(\text{conc-trail } S) \models_{\text{asm}} \text{clauses } S \Rightarrow$
mset-cls C $\notin \text{set } (\text{get-all-mark-of-propagated } (\text{conc-trail } S)) \Rightarrow$
mset-cls C $\notin \# \text{conc-init-clss S} \Rightarrow$
T $\sim \text{remove-cls C S} \Rightarrow$
forget S T

inductive-cases *forgetE*: *forget S T*

inductive *cdcl_W-abs-rf* :: '*st* \Rightarrow '*st* \Rightarrow bool **for** *S* :: '*st* **where**

restart: *restart-abs S T* \Rightarrow *cdcl_W-abs-rf S T* |

forget: *forget-abs S T* \Rightarrow *cdcl_W-abs-rf S T*

inductive *cdcl_W-abs-bj* :: '*st* \Rightarrow '*st* \Rightarrow bool **where**

skip: *skip-abs S S'* \Rightarrow *cdcl_W-abs-bj S S'* |

resolve: *resolve-abs S S'* \Rightarrow *cdcl_W-abs-bj S S'* |

backtrack: *backtrack-abs S S'* \Rightarrow *cdcl_W-abs-bj S S'*

inductive-cases *cdcl_W-abs-bjE*: *cdcl_W-abs-bj S T*

lemma *cdcl_W-abs-bj-cdcl_W-abs-bj*:

cdcl_W-mset.cdcl_W-all-struct-inv (state S) \Rightarrow
cdcl_W-mset.cdcl_W-bj (state S) (state T) \longleftrightarrow *cdcl_W-abs-bj S T*
by (*auto simp*: *cdcl_W-mset.cdcl_W-bj.simps cdcl_W-abs-bj.simps*
backtrack-backtrack-abs skip-skip-abs resolve-resolve-abs)

interpretation *cdcl_W-abs-bj*: *relation-relation-abs cdcl_W-mset.cdcl_W-bj cdcl_W-abs-bj state*

cdcl_W-mset.cdcl_W-all-struct-inv

apply *unfold-locales*

apply (*simp add*: *cdcl_W-abs-bj-cdcl_W-abs-bj*)

apply (*metis (no-types, hide-lams) backtrack-exists-backtrack-abs-step cdcl_W-abs-bj.simps*
cdcl_W-mset.cdcl_W-bj.simps resolve-exists-resolve-abs skip-abs.relation-compatible-abs)

using *cdcl_W-mset.bj cdcl_W-mset.cdcl_W-all-struct-inv-inv cdcl_W-mset.other* **by** *blast*

inductive *cdcl_W-abs-o* :: '*st* \Rightarrow '*st* \Rightarrow bool **for** *S* :: '*st* **where**

decide: *decide-abs S S'* \Rightarrow *cdcl_W-abs-o S S'* |

bj: *cdcl_W-abs-bj S S'* \Rightarrow *cdcl_W-abs-o S S'*

inductive *cdcl_W-abs* :: '*st* \Rightarrow '*st* \Rightarrow bool **for** *S* :: '*st* **where**

propagate: *propagate-abs S S'* \Rightarrow *cdcl_W-abs S S'* |

conflict: *conflict-abs S S'* \Rightarrow *cdcl_W-abs S S'* |

other: *cdcl_W-abs-o S S'* \Rightarrow *cdcl_W-abs S S'* |

rf: *cdcl_W-abs-rf S S'* \Rightarrow *cdcl_W-abs S S'*

7.2.5 Higher level strategy

The rules described previously do not lead to a conclusive state. We have add a strategy and show the inclusion in the multiset version.

inductive $cdcl_W\text{-merge-abs-cp} :: 'st \Rightarrow 'st \Rightarrow \text{bool}$ **for** $S :: 'st$ **where**
conflict': $\text{conflict-abs } S \ T \Longrightarrow \text{full } cdcl_W\text{-abs-bj } T \ U \Longrightarrow cdcl_W\text{-merge-abs-cp } S \ U \mid$
propagate': $\text{propagate-abs}^{++} \ S \ S' \Longrightarrow cdcl_W\text{-merge-abs-cp } S \ S'$

lemma $cdcl_W\text{-merge-cp-cdcl}_W\text{-abs-merge-cp}$:

assumes

$cp: cdcl_W\text{-merge-abs-cp } S \ T$ **and**

$inv: cdcl_W\text{-mset.cdcl}_W\text{-all-struct-inv (state } S)$

shows $cdcl_W\text{-mset.cdcl}_W\text{-merge-cp (state } S) (state \ T)$

using cp

proof (*induction rule: $cdcl_W\text{-merge-abs-cp.induct}$*)

case ($\text{conflict}' \ T \ U$) **note** $\text{confl} = \text{this}(1)$ **and** $\text{bj} = \text{this}(2)$

then have $cdcl_W\text{-mset.conflict (state } S) (state \ T)$

by (*auto simp: conflict-conflict-abs propagate-propagate-abs $cdcl_W\text{-abs-bj-cdcl}_W\text{-abs-bj}$*)

moreover

have $cdcl_W\text{-mset.cdcl}_W\text{-all-struct-inv (state } T)$

using $cdcl_W\text{-mset.conflict } cdcl_W\text{-mset.cdcl}_W\text{-all-struct-inv-inv } \text{confl } inv$

unfolding $\text{conflict-conflict-abs[symmetric]}$ **by** *blast*

then have $\text{full } cdcl_W\text{-mset.cdcl}_W\text{-bj (state } T) (state \ U)$

using bj **by** (*auto simp: $cdcl_W\text{-abs-bj.full-if-full-abs}$*)

ultimately show $?case$ **by** (*auto intro: $cdcl_W\text{-mset.cdcl}_W\text{-merge-cp.intros}$*)

next

case ($\text{propagate}' \ T$)

then show $?case$

by (*auto simp: propagate-abs.tranclp-abs-tranclp intro: $cdcl_W\text{-mset.cdcl}_W\text{-merge-cp.propagate}'$*)

qed

lemma $cdcl_W\text{-merge-cp-abs-exists-cdcl}_W\text{-merge-cp}$:

assumes

$cp: cdcl_W\text{-mset.cdcl}_W\text{-merge-cp (state } S) \ T$ **and**

$inv: cdcl_W\text{-mset.cdcl}_W\text{-all-struct-inv (state } S)$

obtains U **where** $cdcl_W\text{-merge-abs-cp } S \ U$ **and** $T \sim_m \text{state } U$

using cp

proof (*induction rule: $cdcl_W\text{-mset.cdcl}_W\text{-merge-cp.induct}$*)

case ($\text{conflict}' \ T \ U$) **note** $\text{confl} = \text{this}(1)$ **and** $\text{bj} = \text{this}(2)$ **and** $\text{that} = \text{this}(3)$

obtain V **where** $SV: \text{conflict-abs } S \ V$ **and** $TV: T \sim_m \text{state } V$

using $\text{conflict-abs.relation-compatible-abs[of state } S \ S] \ \text{confl}$ **by** *blast*

have $inv\text{-}V: cdcl_W\text{-mset.cdcl}_W\text{-all-struct-inv (state } V)$ **and**

$inv\text{-}T: cdcl_W\text{-mset.cdcl}_W\text{-all-struct-inv } T$

using $TV \ \text{bj } cdcl_W\text{-mset.cdcl}_W\text{-stgy.simps } cdcl_W\text{-mset.cdcl}_W\text{-stgy-cdcl}_W\text{-all-struct-inv}$

$cdcl_W\text{-mset.conflict-is-full1-cdcl}_W\text{-cp } \text{confl } inv$ **unfolding** $cdcl_W\text{-mset-state-eq-eq}$ **by** *blast+*

then obtain T' **where** $\text{full } cdcl_W\text{-abs-bj } V \ T'$ **and** $U \sim_m \text{state } T'$

using $TV \ \text{bj } cdcl_W\text{-abs-bj.full-exists-full-abs[of } V \ U]$ **unfolding** $cdcl_W\text{-mset-state-eq-eq}$

by *blast*

then show $?thesis$ **using** $\text{that } cdcl_W\text{-merge-abs-cp.conflict'[of } S \ V \ T]$ SV **by** *fast*

next

case ($\text{propagate}' \ T$)

then show $?case$

using $cdcl_W\text{-merge-abs-cp.propagate}'$

$\text{propagate-abs.tranclp-relation-tranclp-relation-abs-compatible}$ **by** *blast*

qed

lemma *no-step-cdcl_W-merge-cp-no-step-cdcl_W-abs-merge-cp*:

assumes

inv: *cdcl_W-mset.cdcl_W-all-struct-inv* (state *S*)

shows *no-step cdcl_W-merge-abs-cp* *S* \longleftrightarrow *no-step cdcl_W-mset.cdcl_W-merge-cp* (state *S*)

(**is** *?abs* \longleftrightarrow *?conc*)

proof

assume *?abs*

show *?conc*

proof (rule *ccontr*)

assume \neg *?thesis*

then obtain *T* **where** *cdcl_W-mset.cdcl_W-merge-cp* (state *S*) *T*

by *blast*

then show *False*

using *cdcl_W-merge-cp-abs-exists-cdcl_W-merge-cp*[of *S T*] (*?abs*) *inv* **by** *auto*

qed

next

assume *?conc*

then show *?abs*

using *cdcl_W-merge-cp-cdcl_W-abs-merge-cp* *inv* **by** *blast*

qed

lemma *cdcl_W-merge-abs-cp-right-compatible*:

cdcl_W-merge-abs-cp *S V* \implies *cdcl_W-mset.cdcl_W-all-struct-inv* (state *S*) \implies

V \sim *W* \implies *cdcl_W-merge-abs-cp* *S W*

proof (induction rule: *cdcl_W-merge-abs-cp.induct*)

case (*conflict'* *T U*) **note** *confl* = *this*(1) **and** *full* = *this*(2) **and** *inv* = *this*(3) **and** *UW* = *this*(4)

have *inv-T*: *cdcl_W-mset.cdcl_W-all-struct-inv* (state *T*)

using *cdcl_W-mset.cdcl_W-stgy.simps cdcl_W-mset.cdcl_W-stgy-cdcl_W-all-struct-inv*

cdcl_W-mset.conflict-is-full1-cdcl_W-cp *confl* *conflict-conflict-abs* *inv* **by** *blast*

then have *full cdcl_W-abs-bj* *T W* \vee (*T* = *U* \wedge *no-step cdcl_W-abs-bj* *T*)

using *cdcl_W-abs-bj.full-right-compatible*[OF - *full UW*] *full* **by** *blast*

then consider

(*full*) *full cdcl_W-abs-bj* *T W* |

(0) *T* = *U* **and** *no-step cdcl_W-abs-bj* *T*

by *blast*

then show *?case*

proof *cases*

case *full*

then show *?thesis* **using** *confl* **by** (*blast intro: cdcl_W-merge-abs-cp.intros*)

next

case 0

then have *conflict-abs* *S W* **and** *no-step cdcl_W-abs-bj* *W*

using *confl UW conflict-abs.relation-right-compatible* **apply** *blast*

using *full unfolding full-def*

by (*metis* (*mono-tags*, *lifting*) 0(1) *UW inv-T cdcl_W-abs-bj-cdcl_W-abs-bj*

cdcl_W-mset-state-eq-eq)

moreover then have *full cdcl_W-abs-bj* *W W*

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

ultimately show *?thesis* **by** (*blast intro: cdcl_W-merge-abs-cp.intros*)

qed

next

case (*propagate'*)

then show *?case* **using** *propagate-abs.tranclp-relation-compatible-eq*

by (*blast intro: cdcl_W-merge-abs-cp.propagate'*)

qed

interpretation *cdcl_W-merge-abs-cp: relation-implied-relation-abs*
cdcl_W-mset.cdcl_W-merge-cp cdcl_W-merge-abs-cp state cdcl_W-mset.cdcl_W-all-struct-inv
apply *unfold-locales*
using *cdcl_W-merge-cp-cdcl_W-abs-merge-cp* **apply** *blast*
using *cdcl_W-merge-cp-abs-exists-cdcl_W-merge-cp* **unfolding** *cdcl_W-mset-state-eq-eq* **apply** *blast*
using *cdcl_W-mset.rtrancp-cdcl_W-all-struct-inv-inv*
cdcl_W-mset.rtrancp-cdcl_W-merge-cp-rtrancp-cdcl_W **apply** *blast*
using *cdcl_W-merge-abs-cp-right-compatible* **unfolding** *cdcl_W-mset-state-eq-eq* **by** *blast*

inductive *cdcl_W-merge-abs-stgy* **for** *S :: 'st* **where**
fw-s-cp: full1 cdcl_W-merge-abs-cp S T \implies cdcl_W-merge-abs-stgy S T |
fw-s-decide: decide-abs S T \implies no-step cdcl_W-merge-abs-cp S \implies full cdcl_W-merge-abs-cp T U
 \implies *cdcl_W-merge-abs-stgy S U*

lemma *cdcl_W-cp-cdcl_W-abs-cp:*
assumes *stgy: cdcl_W-merge-abs-stgy S T* **and**
inv: cdcl_W-mset.cdcl_W-all-struct-inv (state S)
shows *cdcl_W-mset.cdcl_W-merge-stgy (state S) (state T)*
using *stgy*
proof (*induction rule: cdcl_W-merge-abs-stgy.induct*)
case (*fw-s-cp T*)
show *?case*
apply (*rule cdcl_W-mset.cdcl_W-merge-stgy.fw-s-cp*)
using *fw-s-cp inv* **by** (*simp add: cdcl_W-merge-abs-cp.full1-iff*)
next
case (*fw-s-decide T U*) **note** *dec = this(1)* **and** *ns = this(2)* **and** *full = this(3)*
have *dec': cdcl_W-mset.decide (state S) (state T)*
using *dec decide-decide-abs* **by** *blast*
then have *cdcl_W-mset.cdcl_W-all-struct-inv (state T)*
using *inv cdcl_W-mset.cdcl_W-all-struct-inv-inv*
by (*blast dest: cdcl_W-mset.cdcl_W.other cdcl_W-mset.cdcl_W-o.decide*)
then have *full cdcl_W-mset.cdcl_W-merge-cp (state T) (state U)*
using *full cdcl_W-merge-abs-cp.full-if-full-abs* **by** *blast*
then show *?case*
using *dec' cdcl_W-mset.cdcl_W-merge-stgy.fw-s-decide[of state S state T state U] ns inv*
by (*simp add: no-step-cdcl_W-merge-cp-no-step-cdcl_W-abs-merge-cp*)
qed

lemma *cdcl_W-merge-abs-stgy-exists-cdcl_W-merge-stgy:*
assumes
inv: cdcl_W-mset.cdcl_W-all-struct-inv S **and**
SS': S \sim_m state S' **and**
st: cdcl_W-mset.cdcl_W-merge-stgy S T
shows $\exists U. \text{cdcl}_W\text{-merge-abs-stgy } S' U \wedge T \sim_m \text{state } U$
using *st*
proof (*induction rule: cdcl_W-mset.cdcl_W-merge-stgy.induct*)
case (*fw-s-cp T*)
then show *?case* **using** *cdcl_W-merge-abs-cp.full1-exists-full1-abs[of S' T] inv*
unfolding *SS'[unfolded cdcl_W-mset-state-eq-eq]* **by** (*metis cdcl_W-merge-abs-stgy.fw-s-cp*)
next
case (*fw-s-decide T U*) **note** *dec = this(1)* **and** *n-s = this(2)* **and** *full = this(3)*
have *SS': S = state S'*
using *SS'* **unfolding** *cdcl_W-mset-state-eq-eq* .

obtain T' **where** $\text{decide-abs } S' \ T'$ **and** TT' : $T \sim_m \text{state } T'$
using $\text{dec decide-abs.relation-compatible-abs[of } S \ S' \ T] \ SS'$ **by** *auto*
moreover
have $\text{cdcl}_W\text{-mset.cdcl}_W\text{-all-struct-inv (state } T')$
using SS' $\text{calculation(1) cdcl}_W\text{-mset.cdcl}_W\text{-intros(3) cdcl}_W\text{-mset.cdcl}_W\text{-all-struct-inv-inv}$
 $\text{cdcl}_W\text{-mset.decide decide-decide-abs inv}$ **by** *blast*
then obtain U' **where** $\text{full cdcl}_W\text{-merge-abs-cp } T' \ U'$ **and** $U \sim_m \text{state } U'$
using $\text{full cdcl}_W\text{-merge-abs-cp.full-exists-full-abs unfolding } TT'[\text{unfolded cdcl}_W\text{-mset-state-eq-eq}]$
by *blast*
moreover have $\text{no-step cdcl}_W\text{-merge-abs-cp } S'$
using $n\text{-s cdcl}_W\text{-merge-abs-cp.no-step-iff inv}$ **unfolding** SS' **by** *blast*
ultimately show $?case$
using $\text{cdcl}_W\text{-merge-abs-stgy.fw-s-decide[of } S' \ T' \ U]$ **by** *fast*
qed

lemma $\text{cdcl}_W\text{-merge-abs-stgy-right-compatible}$:

assumes

$\text{inv: cdcl}_W\text{-mset.cdcl}_W\text{-all-struct-inv (state } S)$ **and**

$\text{st: cdcl}_W\text{-merge-abs-stgy } S \ T$ **and**

$TU: T \sim V$

shows $\text{cdcl}_W\text{-merge-abs-stgy } S \ V$

using $\text{st } TU$

proof (*induction rule: cdcl_W-merge-abs-stgy.induct*)

case ($\text{fw-s-cp } T$)

then show $?thesis$

using $\text{cdcl}_W\text{-merge-abs-cp.full1-right-compatible cdcl}_W\text{-merge-abs-stgy.fw-s-cp inv}$ **by** *blast*

next

case ($\text{fw-s-decide } T \ U$) **note** $\text{dec} = \text{this(1)}$ **and** $n\text{-s} = \text{this(2)}$ **and** $\text{full} = \text{this(3)}$ **and** $UV = \text{this(4)}$

have $\text{inv-T: cdcl}_W\text{-mset.cdcl}_W\text{-all-struct-inv (state } T)$

using $\text{dec inv cdcl}_W\text{-mset.cdcl}_W\text{-all-struct-inv-inv[of state } S \ \text{state } T]$

by (*auto dest!: cdcl_W-mset.cdcl_W-o.decide cdcl_W-mset.cdcl_W.other simp: decide-decide-abs[symmetric]*)

then have $\text{full cdcl}_W\text{-merge-abs-cp } T \ V \vee (T = U \wedge \text{no-step cdcl}_W\text{-merge-abs-cp } T)$

using $\text{cdcl}_W\text{-merge-abs-cp.full-right-compatible[of } T \ U \ V]$ $\text{full } UV$ **by** *blast*

then consider

(*full*) $\text{full cdcl}_W\text{-merge-abs-cp } T \ V$ |

(*0*) $T = U$ **and** $\text{no-step cdcl}_W\text{-merge-abs-cp } T$

by *blast*

then show $?case$

proof *cases*

case *full*

then show $?thesis$

using $n\text{-s dec by (blast intro: cdcl}_W\text{-merge-abs-stgy.intros)}$

next

case *0* **note** $TU = \text{this(1)}$ **and** $n\text{-s}' = \text{this(2)}$

have $\text{decide-abs } S \ V$

using $TU \ \text{dec } UV \ \text{decide-abs.relation-abs-right-compatible}$ **by** *auto*

moreover

have $\text{cdcl}_W\text{-mset.cdcl}_W\text{-all-struct-inv (state } V)$

using $\text{inv-T by (metis (full-types) } TU \ \text{cdcl}_W\text{-mset-state-eq-eq fw-s-decide.prem)}$

then have $\text{full cdcl}_W\text{-merge-abs-cp } V \ V$

using $n\text{-s}' \ TU \ UV[\text{unfolded cdcl}_W\text{-mset-state-eq-eq}]$

unfolding $\text{full-def by (metis cdcl}_W\text{-merge-abs-cp.no-step-iff rtranclp-unfold)}$

ultimately show $?thesis$ **using** $n\text{-s by (blast intro: cdcl}_W\text{-merge-abs-stgy.intros)}$

qed

qed

```

interpretation cdclW-merge-abs-stgy: relation-implied-relation-abs
  cdclW-mset.cdclW-merge-stgy cdclW-merge-abs-stgy state cdclW-mset.cdclW-all-struct-inv
apply unfold-locales
  using cdclW-cp-cdclW-abs-cp apply blast
  using cdclW-merge-abs-stgy-exists-cdclW-merge-stgy apply blast
using cdclW-mset.cdclW-merge-stgy-rtrancpl-cdclW cdclW-mset.rtrancpl-cdclW-all-struct-inv-inv
apply blast
using cdclW-merge-abs-stgy-right-compatible by blast

lemma cdclW-merge-abs-stgy-final-State-conclusive:
  fixes T :: 'st
  assumes
    full: full cdclW-merge-abs-stgy (conc-init-state N) T and
    n-d: distinct-mset-mset (mset-cls N)
  shows (conc-conflicting T = Some {#} ∧ unsatisfiable (set-mset (mset-cls N)))
    ∨ (conc-conflicting T = None ∧ conc-trail T ⊨asm mset-cls N
      ∧ satisfiable (set-mset (mset-cls N)))
proof –
  have cdclW-mset.cdclW-all-struct-inv (state (conc-init-state N))
    using n-d unfolding cdclW-mset.cdclW-all-struct-inv-def by (auto simp: state-conc-init-state)
  then show ?thesis
    using cdclW-mset.full-cdclW-merge-stgy-final-state-conclusive'[of mset-cls N state T]
      cdclW-merge-abs-stgy.full-if-full-abs[of conc-init-state N T] full
    by (auto simp: state-conc-init-state n-d)
qed

end

end

```

7.3 2-Watched-Literal

```

theory CDCL-Two-Watched-Literals
imports CDCL-W-Abstract-State
begin

```

First we define here the core of the two-watched literal data structure:

1. A clause is composed of (at most) two watched literals.
2. It is sufficient to find the candidates for propagation and conflict from the clauses such that the new literal is watched.

While this is the principle behind the two-watched literals, an implementation has to remember the candidates that have been found so far while updating the data structure.

We will directly on the two-watched literals data structure with lists: it could be also seen as a state over some abstract clause representation we would later refine as lists. However, as we need a way to select element from a clause, working on lists is better.

7.3.1 Essence of 2-WL

Data structure 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 literal list*) (*unwatched*: *'v literal list*)

datatype *'v twl-state* =

TWL-State (*raw-trail*: (*'v, 'v twl-clause*) *ann-lits*)
 (*raw-init-clss*: *'v twl-clause list*)
 (*raw-learned-clss*: *'v twl-clause list*) (*backtrack-lvl*: *nat*)
 (*raw-conflicting*: *'v literal list option*)

fun *mmset-of-mlit* :: (*'v, 'v twl-clause*) *ann-lit* \Rightarrow (*'v, 'v clause*) *ann-lit*

where

mmset-of-mlit (*Propagated L C*) = *Propagated L* (*mset* (*watched C @ unwatched C*)) |
mmset-of-mlit (*Decided L*) = *Decided L*

lemma *lit-of-mmset-of-mlit[simp]*: *lit-of* (*mmset-of-mlit x*) = *lit-of x*

by (*cases x*) *auto*

lemma *lits-of-mmset-of-mlit[simp]*: *lits-of* (*mmset-of-mlit ' S*) = *lits-of S*

by (*auto simp: lits-of-def image-image*)

abbreviation *trail* **where**

trail S \equiv *map mmset-of-mlit* (*raw-trail S*)

abbreviation *clauses-of-l* **where**

clauses-of-l \equiv $\lambda L. \text{mset } (\text{map } \text{mset } L)$

definition *raw-clause* :: *'v twl-clause* \Rightarrow *'v literal list* **where**

raw-clause C \equiv *watched C @ unwatched C*

definition *clause* :: *'v twl-clause* \Rightarrow *'v clause* **where**

clause C \equiv *mset* (*raw-clause C*)

lemma *clause-def-lambda*:

clause = ($\lambda C. \text{mset } (\text{raw-clause } C)$)

by (*auto simp: clause-def*)

abbreviation *raw-clss-l* :: *'a twl-clause list* \Rightarrow *'a clauses* **where**

raw-clss-l C \equiv *mset* (*map clause C*)

abbreviation *raw-clauses* :: *'v twl-state* \Rightarrow *'v twl-clause list* **where**

raw-clauses S \equiv *raw-init-clss S @ raw-learned-clss S*

abbreviation *raw-clss* :: *'v twl-state* \Rightarrow *'v clauses* **where**

raw-clss S \equiv *raw-clss-l* (*raw-clauses S*)

interpretation *raw-cl* *clause* .

lemma *mset-map-clause-remove1-cond*:

raw-clss-l (*remove1-cond* ($\lambda D. \text{clause } D = \text{clause } a$) *Cs*) = *remove1-mset* (*clause a*) (*raw-clss-l Cs*)
apply (*induction Cs*)

```

    apply simp
  by (auto simp: ac-simps remove1-mset-single-add raw-clause-def clause-def)

interpretation raw-clss
  clause
  raw-clss-l
  λL C. L ∈ set C op #
  apply (unfold-locales)
  using mset-map-clause-remove1-cond by (auto simp: hd-map comp-def map-tl ac-simps raw-clause-def
    union-mset-list mset-map-mset-remove1-cond ex-mset clause-def-lambda)

lemma ex-mset-unwatched-watched:
  ∃ a. mset (unwatched a) + mset (watched a) = E
proof -
  obtain e where mset e = E
  using ex-mset by blast
  then have mset (unwatched (TWL-Clause [] e)) + mset (watched (TWL-Clause [] e)) = E
  by auto
  then show ?thesis by fast
qed

abbreviation conc-learned-clss where
  conc-learned-clss ≡ λS. mset (map clause (raw-learned-clss S))

interpretation twl: abs-stateW-ops
  clause
  raw-clss-l
  λL C. L ∈ set C op #

  mset

  raw-clause λC. TWL-Clause [] C
  trail λS. hd (raw-trail S)
  (λS. raw-init-clss S @ raw-learned-clss S) backtrack-lvl raw-conflicting
  conc-learned-clss
  rewrites
    twl.mmset-of-mlit = mmset-of-mlit
proof goal-cases
  case 1
  show H: ?case
  apply unfold-locales apply (auto simp: hd-map comp-def map-tl ac-simps raw-clause-def
    mset-map-mset-remove1-cond ex-mset-unwatched-watched clause-def)[3]
  using mset-map-mset-remove1-cond
  done

  case 2
  show ?case
  apply (rule ext)
  apply (rename-tac x)
  apply (case-tac x)
  apply (simp-all add: abs-stateW-ops.mmset-of-mlit.simps[OF H] raw-clause-def clause-def)
  done
qed

declare CDCL-Two-Watched-Literals.twl.mset-ccls-ccls-of-cl[simp del]

```


definition

$candidates-propagate :: 'v\ twl-state \Rightarrow ('v\ literal \times 'v\ twl-clause)\ set$

where

$candidates-propagate\ S =$
 $\{(L, C) \mid L\ C.$
 $C \in set\ (raw-clauses\ S) \wedge$
 $set\ (watched\ C) - (uminus\ ' lits-of-l\ (trail\ S)) = \{L\} \wedge$
 $undefined-lit\ (raw-trail\ S)\ L\}$

definition $candidates-conflict :: 'v\ twl-state \Rightarrow 'v\ twl-clause\ set$ **where**

$candidates-conflict\ S =$
 $\{C. C \in set\ (raw-clauses\ S) \wedge$
 $set\ (watched\ C) \subseteq uminus\ ' lits-of-l\ (raw-trail\ S)\}$

primrec $(nonexhaustive)\ index :: 'a\ list \Rightarrow 'a \Rightarrow nat$ **where**

$index\ (a \# l)\ c = (if\ a = c\ then\ 0\ else\ 1 + index\ l\ c)$

lemma $index-nth$:

$a \in set\ l \implies l!\ (index\ l\ a) = a$
by $(induction\ l)\ auto$

Invariants

The structural invariants states that there are at most two watched elements, that the watched literals are distinct, and that there are 2 watched literals if there are at least than two different literals in the full clauses.

primrec $struct-wf-tw-cl :: 'v\ twl-clause \Rightarrow bool$ **where**

$struct-wf-tw-cl\ (TWL-Clause\ W\ UW) \longleftrightarrow$
 $distinct\ W \wedge length\ W \leq 2 \wedge (length\ W < 2 \longrightarrow set\ UW \subseteq set\ W)$

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*, L does not get swapped with a watched literal L' such that $-L'$ is in the trail. This corresponds to the laziness of the data structure.

Remark that M is a trail: literals at the end were the first to be added to the trail.

primrec $watched-only-lazy-updates :: ('v, 'mark)\ ann-lits \Rightarrow$

$'v\ twl-clause \Rightarrow bool$

where

$watched-only-lazy-updates\ M\ (TWL-Clause\ W\ UW) \longleftrightarrow$
 $(\forall L' \in set\ W. \forall L \in set\ UW.$
 $-L' \in lits-of-l\ M \longrightarrow -L \in lits-of-l\ M \longrightarrow L \notin set\ W \longrightarrow$
 $index\ (map\ lit-of\ M)\ (-L') \leq index\ (map\ lit-of\ M)\ (-L))$

If the negation of a watched literal is included in the trail, then the negation of every unwatched literals is also included in the trail. Otherwise, the data-structure has to be updated.

primrec $watched-wf-tw-cl :: ('a, 'b)\ ann-lits \Rightarrow 'a\ twl-clause \Rightarrow$

$bool$ **where**

$watched-wf-tw-cl\ M\ (TWL-Clause\ W\ UW) \longleftrightarrow$
 $(\forall L \in set\ W. -L \in lits-of-l\ M \longrightarrow (\forall L' \in set\ UW. L' \notin set\ W \longrightarrow -L' \in lits-of-l\ M))$

Here are the invariant strictly related to the 2-WL data structure.

primrec $wf-tw-cl :: ('v, 'mark)\ ann-lits \Rightarrow 'v\ twl-clause \Rightarrow bool$ **where**

$wf-tw-cl\ M\ (TWL-Clause\ W\ UW) \longleftrightarrow$

*struct-wf-twl-cl*s (TWL-Clause W UW) \wedge *watched-wf-twl-cl*s M (TWL-Clause W UW) \wedge
watched-only-lazy-updates M (TWL-Clause W UW)

lemma *wf-twl-cl*s-annotation-independant:

assumes M: *map lit-of* M = *map lit-of* M'

shows *wf-twl-cl*s M (TWL-Clause W UW) \longleftrightarrow *wf-twl-cl*s M' (TWL-Clause W UW)

proof –

have *lits-of-l* M = *lits-of-l* 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-cl*s-*wf-twl-cl*s-tl:

assumes wf: *wf-twl-cl*s M C **and** n-d: *no-dup* M

shows *wf-twl-cl*s (tl M) C

proof (*cases* M)

case Nil

then show ?thesis **using** wf

by (*cases* C) (*simp add: wf-twl-cl.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 \in set W **and**

LM: \neg L \in *lits-of-l* M' **and**

L'UW: L' \in set UW **and**

L' \notin set W

then have

L'M: \neg L' \in *lits-of-l* M

using wf **by** (*auto simp: C M*)

have *watched-only-lazy-updates* M C

using wf **by** (*auto simp: C*)

then have

index (*map lit-of* M) (\neg L) \leq *index* (*map lit-of* M) (\neg L')

using LM L'M L'UW LW \langle L' \notin set W \rangle C M **unfolding** *lits-of-def*

by (*fastforce simp: lits-of-def*)

then have \neg L' \in *lits-of-l* M'

using \langle L' \notin set W \rangle LW L'M **by** (*auto simp: C M split: if-split-asm*)

}

moreover

{

fix L' L

assume

L' \in set W **and**

L \in set UW **and**

L'M: \neg L' \in *lits-of-l* M' **and**

\neg L \in *lits-of-l* M' **and**

L \notin set W

moreover

have *lit-of* l \neq \neg L'

using n-d **unfolding** M

by (*metis* (*no-types*) L'M M *Decided-Propagated-in-iff-in-lits-of-l* *defined-lit-map*
distinct.simps(2) *list.simps*(9) *set-map*)

moreover have *watched-only-lazy-updates* $M\ C$
using *wf* **by** (*auto simp*: C)
ultimately have $\text{index } (\text{map lit-of } M') (-\ L') \leq \text{index } (\text{map lit-of } M') (-\ L)$
by (*fastforce simp*: $M\ C$ *split*: *if-split-asm*)
}
moreover have *distinct* W **and** $\text{length } W \leq 2$ **and** $(\text{length } W < 2 \longrightarrow \text{set } UW \subseteq \text{set } W)$
using *wf* **by** (*auto simp*: $C\ M$)
ultimately show *?thesis* **by** (*auto simp add*: $M\ C$)
qed

lemma *wf-twl-cls-append*:

assumes
 $n\text{-d}: \text{no-dup } (M' @ M)$ **and**
 $wf: wf\text{-twl-cls } (M' @ M)\ C$
shows $wf\text{-twl-cls } M\ C$
using *wf n-d* **apply** (*induction* M')
apply *simp*
using *wf-twl-cls-wf-twl-cls-tl* **by** *fastforce*

definition *wf-twl-state* :: ' $v\ twl\text{-state} \Rightarrow \text{bool}$ **where**

$wf\text{-twl-state } S \longleftrightarrow$
 $(\forall C \in \text{set } (\text{raw-clauses } S). wf\text{-twl-cls } (\text{raw-trail } S)\ C) \wedge \text{no-dup } (\text{raw-trail } S)$

lemma *wf-candidates-propagate-sound*:

assumes $wf: wf\text{-twl-state } S$ **and**
 $\text{cand}: (L, C) \in \text{candidates-propagate } S$
shows $\text{raw-trail } S \models_{as} C\text{Not } (\text{mset } (\text{removeAll } L\ (\text{raw-clause } C))) \wedge \text{undefined-lit } (\text{raw-trail } S)\ L$
(is *?Not* \wedge *?undef***)**

proof

def $M \equiv \text{raw-trail } S$
def $N \equiv \text{raw-init-clss } S$
def $U \equiv \text{raw-learned-clss } S$

note $MNU\text{-defs } [simp] = M\text{-def } N\text{-def } U\text{-def}$

have *cw*:

$C \in \text{set } (N @ U)$
 $\text{set } (\text{watched } C) - \text{uminus } \text{' lits-of-l } M = \{L\}$
 $\text{undefined-lit } M\ L$
using *cand* **unfolding** *candidates-propagate-def MNU-defs* **by** *auto*

obtain $W\ UW$ **where** *cw-eq*: $C = \text{TWL-Clause } W\ UW$

by (*cases* C)

have *l-w*: $L \in \text{set } W$

using *cw(2)* *cw-eq* **by** *auto*

have *wf-c*: $wf\text{-twl-cls } M\ C$

using *wf cw(1)* **unfolding** *wf-twl-state-def* **by** *simp*

have *w-nw*:

$\text{distinct } W$
 $\text{length } W < 2 \implies \text{set } UW \subseteq \text{set } W$
 $\bigwedge L\ L'. L \in \text{set } W \implies -L \in \text{lits-of-l } M \implies L' \in \text{set } UW \implies L' \notin \text{set } W \implies -L' \in \text{lits-of-l } M$
using *wf-c* **unfolding** *cw-eq* **by** (*auto simp*: *image-image*)

```

have  $\forall L' \in \text{set (raw-clause } C) - \{L\}. -L' \in \text{lits-of-l } M$ 
proof (cases length  $W < 2$ )
  case True
  moreover have size  $W \neq 0$ 
    using cw(2) cw-eq by auto
  ultimately have size  $W = 1$ 
    by linarith
  then have w:  $W = [L]$ 
    using l-w by (auto simp: length-list-Suc-0)
  from True have set  $UW \subseteq \text{set } W$ 
    using w-nw(2) by blast
  then show ?thesis
    using w cw(1) cw-eq by (auto simp: raw-clause-def)
next
case sz2: False
show ?thesis
proof
  fix  $L'$ 
  assume l':  $L' \in \text{set (raw-clause } C) - \{L\}$ 
  have ex-la:  $\exists La. La \neq L \wedge La \in \text{set } W$ 
  proof (cases  $W$ )
    case w: Nil
    then show ?thesis
      using l-w by auto
  next
    case lb: (Cons Lb  $W'$ )
    show ?thesis
    proof (cases  $W'$ )
      case Nil
      then show ?thesis
        using lb sz2 by simp
    next
      case lc: (Cons Lc  $W''$ )
      then show ?thesis
        by (metis distinct-length-2-or-more lb list.set-intros(1) list.set-intros(2) w-nw(1))
    qed
  qed
  then obtain La where la:  $La \neq L \wedge La \in \text{set } W$ 
    by blast
  then have La  $\in \text{uminus ' lits-of-l } M$ 
    using cw(2)[unfolded cw-eq, simplified, folded M-def]  $\langle La \in \text{set } W \rangle \langle La \neq L \rangle$  by auto
  then have nla:  $-La \in \text{lits-of-l } M$ 
    by (auto simp: image-image)
  then show  $-L' \in \text{lits-of-l } M$ 

proof -
  have f1:  $L' \in \text{set (raw-clause } C)$ 
    using l' by blast
  have f2:  $L' \notin \{L\}$ 
    using l' by fastforce
  have  $\bigwedge l L. - (l::'a \text{ literal}) \in L \vee l \notin \text{uminus ' } L$ 
    by force
  then show ?thesis
    using cw(1) cw-eq w-nw(3) raw-clause-def by (metis DiffI Un-iff cw(2) f1 f2 la(2) nla
      set-append twl-clause.sel(1) twl-clause.sel(2))
qed

```

```

qed
qed
then show ?Not
  unfolding true-annots-def by (auto simp: image-image Ball-def CNot-def)

show ?undef
  using cw(3) unfolding M-def by blast
qed

lemma wf-candidates-propagate-complete:
  assumes wf: wf-twl-state S and
    c-mem:  $C \in \text{set (raw-clauses } S)$  and
    l-mem:  $L \in \text{set (raw-clause } C)$  and
    unsat:  $\text{trail } S \models_{\text{as}} \text{CNot (mset-set (set (raw-clause } C) - \{L\}))}$  and
    undef:  $\text{undefined-lit (raw-trail } S) L$ 
  shows  $(L, C) \in \text{candidates-propagate } S$ 
proof -
  def M  $\equiv$  raw-trail S
  def N  $\equiv$  raw-init-clss S
  def U  $\equiv$  raw-learned-clss S

  note MNU-defs [simp] = M-def N-def U-def

  obtain W UW where cw-eq:  $C = \text{TWL-Clause } W UW$ 
    by (cases C, blast)

  have wf-c: wf-twl-clss M C
    using wf c-mem unfolding wf-twl-state-def by simp

  have w-nw:
    distinct W
    length W < 2  $\implies$   $\text{set } UW \subseteq \text{set } W$ 
     $\bigwedge L L'. L \in \text{set } W \implies -L \in \text{lits-of-l } M \implies L' \in \text{set } UW \implies L' \notin \text{set } W \implies -L' \in \text{lits-of-l } M$ 
    using wf-c unfolding cw-eq by (auto simp: image-image)

  have unit-set:  $\text{set } W - (\text{uminus ' lits-of-l } M) = \{L\}$  (is ?W = ?L)
proof
  show ?W  $\subseteq \{L\}$ 
proof
  fix L'
  assume l':  $L' \in ?W$ 
  then have l'-mem-w:  $L' \in \text{set } W$ 
    by (simp add: in-diffD)
  have  $L' \notin \text{uminus ' lits-of-l } M$ 
    using l' by blast
  then have  $\neg M \models_a \{\# - L' \#\}$ 
    by (auto simp: lits-of-def uminus-lit-swap image-image)
  moreover have  $L' \in \text{set (raw-clause } C)$ 
    using c-mem cw-eq l'-mem-w by (auto simp: raw-clause-def)
  ultimately have  $L' = L$ 
    using unsat[unfolded CNot-def true-annots-def, simplified]
    unfolding M-def by fastforce
  then show  $L' \in \{L\}$ 
    by simp
qed
next

```

```

show  $\{L\} \subseteq ?W$ 
proof clarify
  have  $L \in \text{set } W$ 
  proof (cases  $W$ )
    case Nil
    then show ?thesis
      using  $w\text{-nw}(2)$   $cw\text{-eq } l\text{-mem}$  by (auto simp: raw-clause-def)
  next
    case (Cons  $La W'$ )
    then show ?thesis
      proof (cases  $La = L$ )
        case True
        then show ?thesis
          using  $Cons$  by simp
      next
        case False
        have  $\neg La \in \text{lits-of-l } M$ 
          using  $False$   $Cons$   $cw\text{-eq } \text{unsat}[\text{unfolded } C\text{Not-def } \text{true-annots-def}, \text{simplified}]$ 
          by (fastforce simp: raw-clause-def)
        then show ?thesis
          using  $Cons$   $cw\text{-eq } l\text{-mem } \text{undef } w\text{-nw}(3)$ 
          by (auto simp: Decided-Propagated-in-iff-in-lits-of-l raw-clause-def)
      qed
    qed
  moreover have  $L \notin \# \text{mset-set } (\text{uminus } ' \text{lits-of-l } M)$ 
    using  $\text{undef}$  by (auto simp: Decided-Propagated-in-iff-in-lits-of-l image-image)
  ultimately show  $L \in ?W$ 
    by simp
  qed
qed

show ?thesis
  unfolding candidates-propagate-def using unit-set undef c-mem unfolding cw-eq M-def
  by (auto simp: image-image cw-eq intro!: exI[of - C])
qed

lemma wf-candidates-conflict-sound:
  assumes wf: wf-twl-state  $S$  and
    cand:  $C \in \text{candidates-conflict } S$ 
  shows  $\text{trail } S \models_{as} C\text{Not } (\text{clause } C) \wedge C \in \text{set } (\text{raw-clauses } S)$ 
proof
  def  $M \equiv \text{raw-trail } S$ 
  def  $N \equiv \text{raw-init-clss } S$ 
  def  $U \equiv \text{raw-learned-clss } S$ 

  note MNU-defs [simp] =  $M\text{-def } N\text{-def } U\text{-def}$ 

  have cw:
     $C \in \text{set } (N @ U)$ 
     $\text{set } (\text{watched } C) \subseteq \text{uminus } ' \text{lits-of-l } (\text{trail } S)$ 
    using cand[unfolded candidates-conflict-def, simplified] by auto

  obtain  $W UW$  where  $cw\text{-eq: } C = \text{TWL-Clause } W UW$ 
    by (cases  $C$ , blast)

  have wf-c: wf-twl-cl  $M C$ 

```

```

using wf cw(1) unfolding wf-twl-state-def by simp

have w-nw:
  distinct W
  length W < 2  $\implies$  set UW  $\subseteq$  set W
   $\bigwedge L L'. L \in \text{set } W \implies -L \in \text{lits-of-l } M \implies L' \in \text{set } UW \implies L' \notin \text{set } W \implies -L' \in \text{lits-of-l } M$ 
using wf-c unfolding cw-eq by (auto simp: image-image)

have  $\forall L \in \text{set } (\text{raw-clause } C). -L \in \text{lits-of-l } M$ 
proof (cases W)
  case Nil
  then have raw-clause C = []
    using cw(1) cw-eq w-nw(2) by (auto simp: raw-clause-def)
  then show ?thesis
    by simp
next
  case (Cons La W') note W' = this(1)
  show ?thesis
  proof
    fix L
    assume l: L  $\in$  set (raw-clause C)
    show -L  $\in$  lits-of-l M
    proof (cases L  $\in$  set W)
      case True
      then show ?thesis
        using cw(2) cw-eq by fastforce
      next
      case False
      then show ?thesis
        using W' cw(2) cw-eq l w-nw(3) unfolding M-def raw-clause-def
        by (metis (no-types, lifting) UnE imageE list.set-intros(1)
          lits-of-mmset-of-mlit rev-subsetD set-append set-map twl-clause.sel(1)
          twl-clause.sel(2) uminus-of-uminus-id)
    qed
  qed
qed
then show trail S  $\models_{\text{as}}$  CNot (clause C)
  unfolding CNot-def true-annots-def clause-def by auto

show C  $\in$  set (raw-clauses S)
  using cw by auto
qed

lemma wf-candidates-conflict-complete:
  assumes wf: wf-twl-state S and
  c-mem: C  $\in$  set (raw-clauses S) and
  unsat: trail S  $\models_{\text{as}}$  CNot (clause C)
  shows C  $\in$  candidates-conflict S
proof -
  def M  $\equiv$  raw-trail S
  def N  $\equiv$  twl.conc-init-clss S
  def U  $\equiv$  conc-learned-clss S

  note MNU-defs [simp] = M-def N-def U-def

  obtain W UW where cw-eq: C = TWL-Clause W UW

```

by (cases C, blast)

have wf-c: wf-twl-cls M C
 using wf-c-mem unfolding wf-twl-state-def by simp

have w-nw:
 distinct W
 length W < 2 \implies set UW \subseteq set W
 $\bigwedge L L'. L \in \text{set } W \implies -L \in \text{lits-of-l } M \implies L' \in \text{set } UW \implies L' \notin \text{set } W \implies -L' \in \text{lits-of-l } M$
 using wf-c unfolding cw-eq by (auto simp: image-image)

have $\bigwedge L. L \in \text{set } (\text{raw-clause } C) \implies -L \in \text{lits-of-l } M$
 unfolding M-def using unsat[unfolded CNot-def true-annots-def, simplified]
 by (auto simp: clause-def)
 then have set (raw-clause C) \subseteq uminus ' lits-of-l M
 by (metis imageI subsetI uminus-of-uminus-id)
 then have set W \subseteq uminus ' lits-of-l M
 using cw-eq by (auto simp: raw-clause-def)
 then have subset: set W \subseteq uminus ' lits-of-l M
 by (simp add: w-nw(1))

have W = watched C
 using cw-eq twl-clause.sel(1) by simp
 then show ?thesis
 using MNU-defs c-mem subset candidates-conflict-def by blast

qed

typedef 'v wf-twl = {S::'v twl-state. wf-twl-state S}
 morphisms rough-state-of-twl twl-of-rough-state
 proof –
 have TWL-State ([::]('v, 'v twl-clause) ann-lits)
 [] [] 0 None \in {S::'v twl-state. wf-twl-state S}
 by (auto simp: wf-twl-state-def)
 then show ?thesis by auto

qed

lemma [code abstype]:
 twl-of-rough-state (rough-state-of-twl S) = S
 by (fact CDCL-Two-Watched-Literals.wf-twl.rough-state-of-twl-inverse)

lemma wf-twl-state-rough-state-of-twl[simp]: wf-twl-state (rough-state-of-twl S)
 using rough-state-of-twl by auto

abbreviation candidates-conflict-twl :: 'v wf-twl \Rightarrow 'v twl-clause set **where**
 candidates-conflict-twl S \equiv candidates-conflict (rough-state-of-twl S)

abbreviation candidates-propagate-twl :: 'v wf-twl \Rightarrow ('v literal \times 'v twl-clause) set **where**
 candidates-propagate-twl S \equiv candidates-propagate (rough-state-of-twl S)

abbreviation raw-trail-twl :: 'a wf-twl \Rightarrow ('a, 'a twl-clause) ann-lits **where**
 raw-trail-twl S \equiv raw-trail (rough-state-of-twl S)

abbreviation trail-twl :: 'a wf-twl \Rightarrow ('a, 'a literal multiset) ann-lits **where**
 trail-twl S \equiv trail (rough-state-of-twl S)

abbreviation raw-clauses-twl :: 'a wf-twl \Rightarrow 'a twl-clause list **where**

raw-clauses-twl $S \equiv \text{raw-clauses } (\text{rough-state-of-twl } S)$

abbreviation *raw-init-clss-twl* $:: 'a \text{ wf-twl} \Rightarrow 'a \text{ twl-clause list}$ **where**
raw-init-clss-twl $S \equiv \text{raw-init-clss } (\text{rough-state-of-twl } S)$

abbreviation *raw-learned-clss-twl* $:: 'a \text{ wf-twl} \Rightarrow 'a \text{ twl-clause list}$ **where**
raw-learned-clss-twl $S \equiv \text{raw-learned-clss } (\text{rough-state-of-twl } S)$

abbreviation *conc-learned-clss-twl* $:: 'a \text{ wf-twl} \Rightarrow 'a \text{ clauses}$ **where**
conc-learned-clss-twl $S \equiv \text{conc-learned-clss } (\text{rough-state-of-twl } S)$

abbreviation *backtrack-lvl-twl* **where**
backtrack-lvl-twl $S \equiv \text{backtrack-lvl } (\text{rough-state-of-twl } S)$

abbreviation *raw-conflicting-twl* **where**
raw-conflicting-twl $S \equiv \text{raw-conflicting } (\text{rough-state-of-twl } S)$

lemma *wf-candidates-twl-conflict-complete*:

assumes

c-mem: $C \in \text{set } (\text{raw-clauses-twl } S)$ **and**

unsat: $\text{trail-twl } S \models_{\text{as}} \text{CNot } (\text{clause } C)$

shows $C \in \text{candidates-conflict-twl } S$

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 $k \ S \equiv$

$\text{TWL-State } (\text{raw-trail } S) (\text{raw-init-clss } S) (\text{raw-learned-clss } S) \ k \ (\text{raw-conflicting } S)$

abbreviation *update-conflicting* **where**

update-conflicting $C \ S \equiv$

$\text{TWL-State } (\text{raw-trail } S) (\text{raw-init-clss } S) (\text{raw-learned-clss } S) (\text{backtrack-lvl } S) \ C$

Abstract 2-WL

definition *tl-trail* **where**

tl-trail $S =$

$\text{TWL-State } (\text{tl } (\text{raw-trail } S)) (\text{raw-init-clss } S) (\text{raw-learned-clss } S) (\text{backtrack-lvl } S)$
 $(\text{raw-conflicting } S)$

locale *abstract-twl* $=$

fixes

watch $:: 'v \text{ twl-state} \Rightarrow 'v \text{ literal list} \Rightarrow 'v \text{ twl-clause}$ **and**

rewatch $:: 'v \text{ literal} \Rightarrow 'v \text{ twl-state} \Rightarrow$

$'v \text{ twl-clause} \Rightarrow 'v \text{ twl-clause}$ **and**

restart-learned $:: 'v \text{ twl-state} \Rightarrow 'v \text{ twl-clause list}$

assumes

clause-watch: $\text{no-dup } (\text{raw-trail } S) \Longrightarrow \text{clause } (\text{watch } S \ C) = \text{mset } C$ **and**

wf-watch: $\text{no-dup } (\text{raw-trail } S) \Longrightarrow \text{wf-twl-cls } (\text{raw-trail } S) (\text{watch } S \ C)$ **and**

clause-rewatch: $\text{clause } (\text{rewatch } L' \ S \ C') = \text{clause } C'$ **and**

wf-rewatch:

$\text{no-dup } (\text{raw-trail } S) \Longrightarrow \text{undefined-lit } (\text{raw-trail } S) (\text{lit-of } L) \Longrightarrow$

$\text{wf-twl-cls } (\text{raw-trail } S) \ C' \Longrightarrow$

$\text{wf-twl-cls } (L \ \# \ \text{raw-trail } S) (\text{rewatch } (\text{lit-of } L) \ S \ C')$

and

restart-learned: $\text{mset } (\text{restart-learned } S) \subseteq \# \ \text{mset } (\text{raw-learned-clss } S)$ — We need *mset* and not *set* to take care of duplicates.

begin

definition

$cons-trail :: ('v, 'v\ twl-clause)\ ann-lit \Rightarrow 'v\ twl-state \Rightarrow 'v\ twl-state$

where

$cons-trail\ L\ S =$
 $TWL-State\ (L\ \# \ raw-trail\ S)\ (map\ (rewatch\ (lit-of\ L)\ S)\ (raw-init-clss\ S))$
 $(map\ (rewatch\ (lit-of\ L)\ S)\ (raw-learned-clss\ S))\ (backtrack-lvl\ S)\ (raw-conflicting\ S)$

definition

$add-init-cls :: 'v\ literal\ list \Rightarrow 'v\ twl-state \Rightarrow 'v\ twl-state$

where

$add-init-cls\ C\ S =$
 $TWL-State\ (raw-trail\ S)\ (watch\ S\ C\ \# \ raw-init-clss\ S)\ (raw-learned-clss\ S)\ (backtrack-lvl\ S)$
 $(raw-conflicting\ S)$

definition

$add-learned-cls :: 'v\ literal\ list \Rightarrow 'v\ twl-state \Rightarrow 'v\ twl-state$

where

$add-learned-cls\ C\ S =$
 $TWL-State\ (raw-trail\ S)\ (raw-init-clss\ S)\ (watch\ S\ C\ \# \ raw-learned-clss\ S)\ (backtrack-lvl\ S)$
 $(raw-conflicting\ S)$

definition

$remove-cls :: 'v\ literal\ list \Rightarrow 'v\ twl-state \Rightarrow 'v\ twl-state$

where

$remove-cls\ C\ S =$
 $TWL-State\ (raw-trail\ S)$
 $(removeAll-cond\ (\lambda D.\ clause\ D =\ mset\ C)\ (raw-init-clss\ S))$
 $(removeAll-cond\ (\lambda D.\ clause\ D =\ mset\ C)\ (raw-learned-clss\ S))$
 $(backtrack-lvl\ S)$
 $(raw-conflicting\ S)$

definition $init-state :: 'v\ literal\ list\ list \Rightarrow 'v\ twl-state$ **where**

$init-state\ N = fold\ add-init-cls\ N\ (TWL-State\ []\ []\ 0\ None)$

lemma *unchanged-fold-add-init-cls:*

$raw-trail\ (fold\ add-init-cls\ Cs\ (TWL-State\ M\ N\ U\ k\ C)) = M$
 $raw-learned-clss\ (fold\ add-init-cls\ Cs\ (TWL-State\ M\ N\ U\ k\ C)) = U$
 $backtrack-lvl\ (fold\ add-init-cls\ Cs\ (TWL-State\ M\ N\ U\ k\ C)) = k$
 $raw-conflicting\ (fold\ add-init-cls\ Cs\ (TWL-State\ M\ N\ U\ k\ C)) = C$
by (*induct Cs arbitrary: N*) (*auto simp: add-init-cls-def*)

lemma *unchanged-init-state[simp]:*

$raw-trail\ (init-state\ N) = []$
 $raw-learned-clss\ (init-state\ N) = []$
 $backtrack-lvl\ (init-state\ N) = 0$
 $raw-conflicting\ (init-state\ N) = None$
unfolding *init-state-def* **by** (*rule unchanged-fold-add-init-cls*)**+**

lemma *conc-init-clss[simp]:*

$twl.conc-init-clss\ (TWL-State\ M\ N\ U\ k\ C) = raw-clss-l\ N$
by (*simp add: twl.conc-init-clss-def*)

lemma *clauses-init-fold-add-init:*

$no-dup\ M \implies$

$twl.conc-init-clss$ (fold $add-init-clss$ Cs ($TWL-State$ M N U k C)) =
 $clauses-of-l$ Cs + $raw-clss-l$ N
by (induct Cs arbitrary: N) (auto simp: $add-init-clss-def$ $clause-watch$ $comp-def$ $ac-simps$
 $clause-def[symmetric]$)

lemma $init-clss-init-state[simp]$: $twl.conc-init-clss$ ($init-state$ N) = $clauses-of-l$ N
unfolding $init-state-def$ **by** (subst $clauses-init-fold-add-init$) $simp-all$

definition $restart'$ **where**
 $restart' S = TWL-State [] (raw-init-clss S) (restart-learned S) 0 None$

end

Instanciacion of the previous locale

definition $watch-nat :: 'v twl-state \Rightarrow 'v literal list \Rightarrow 'v twl-clause$ **where**
 $watch-nat S C =$
 (let
 $C' = remdups C;$
 $neg-not-assigned = filter (\lambda L. \neg L \in lits-of-l (raw-trail S)) C';$
 $neg-assigned-sorted-by-trail = filter (\lambda L. L \in set C) (map (\lambda L. \neg lit-of L) (raw-trail S));$
 $W = take\ 2 (neg-not-assigned @ neg-assigned-sorted-by-trail);$
 $UW = foldr remove1 W C$
 in $TWL-Clause W UW$)

lemma $list-cases2$:
fixes $l :: 'a list$
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 $\forall x \in set\ l. x \in set\ P \wedge Q\ x$
using $assms$ **by** $auto$

lemma $no-dup-filter-diff$:
assumes $n-d$: $no-dup\ M$ **and** H : $[L \leftarrow map (\lambda L. \neg lit-of L) M. L \in set\ C] = l$
shows $distinct\ l$
unfolding $H[symmetric]$
apply (rule $distinct-filter$)
using $n-d$ **by** (induction M) $auto$

lemma $watch-nat-lists-disjointD$:
assumes
 l : $[L \leftarrow remdups\ C. \neg L \in lits-of-l (raw-trail S)] = l$ **and**
 l' : $[L \leftarrow map (\lambda L. \neg lit-of L) (raw-trail S) \ .\ L \in set\ C] = l'$
shows $\forall x \in set\ l. \forall y \in set\ l'. x \neq y$
by (auto simp: $l[symmetric]$ $l'[symmetric]$ $lits-of-def$ $image-image$)

lemma $watch-nat-list-cases-witness[consumes\ 2, case-names\ Nil-Nil\ Nil-single\ Nil-other\ single-Nil\ single-other\ other]$:
fixes

$C :: 'v \text{ literal list}$ **and**
 $S :: 'v \text{ twl-state}$
defines
 $xs \equiv [L \leftarrow \text{remdups } C. - L \notin \text{lits-of-l (raw-trail } S)]$ **and**
 $ys \equiv [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) \text{ (raw-trail } S) . L \in \text{set } C]$
assumes
 $n\text{-d: no-dup (raw-trail } S)$ **and**
 $Nil\text{-Nil: } xs = [] \implies ys = [] \implies P$ **and**
 $Nil\text{-single:}$
 $\bigwedge a. xs = [] \implies ys = [a] \implies a \in \text{set } C \implies P$ **and**
 $Nil\text{-other: } \bigwedge a \ b \ ys'. xs = [] \implies ys = a \# b \# ys' \implies a \neq b \implies P$ **and**
 $single\text{-Nil: } \bigwedge a. xs = [a] \implies ys = [] \implies P$ **and**
 $single\text{-other: } \bigwedge a \ b \ ys'. xs = [a] \implies ys = b \# ys' \implies a \neq b \implies P$ **and**
 $other: \bigwedge a \ b \ xs'. xs = a \# b \# xs' \implies a \neq b \implies P$
shows P
proof –
note $xs\text{-def}[simp]$ **and** $ys\text{-def}[simp]$
have $dist: \bigwedge P. \text{distinct } [L \leftarrow \text{remdups } C . P \ L]$
by $auto$
then have $H: \bigwedge a \ b \ P \ xs. [L \leftarrow \text{remdups } C . P \ L] = a \# b \# xs \implies a \neq b$
by $(metis \text{distinct-length-2-or-more})$
show $?thesis$
apply $(\text{cases } [L \leftarrow \text{remdups } C. - L \notin \text{lits-of-l (raw-trail } S)])$
 $\text{rule: list-cases2;}$
 $\text{cases } [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) \text{ (raw-trail } S) . L \in \text{set } C] \text{ rule: list-cases2})$
using $Nil\text{-Nil}$ **apply** $simp$
using $Nil\text{-single}$ **apply** $(\text{force dest: filter-in-list-prop-verifiedD})$
using $Nil\text{-other no-dup-filter-diff}[OF \ n\text{-d, of } C]$
apply $fastforce$
using $single\text{-Nil}$ **apply** $simp$
using $single\text{-other } xs\text{-def } ys\text{-def}$ **apply** $(metis \text{list.set-intros(1) watch-nat-lists-disjointD})$
using $single\text{-other unfolding } xs\text{-def } ys\text{-def}$ **apply** $(metis \text{list.set-intros(1) watch-nat-lists-disjointD})$
using $other \ xs\text{-def } ys\text{-def}$ **by** $(metis \ H)+$
qed

lemma $watch\text{-nat-list-cases}$ $[\text{consumes } 1, \text{case-names } Nil\text{-Nil } Nil\text{-single } Nil\text{-other } single\text{-Nil } single\text{-other } other]:$
fixes
 $C :: 'v \text{ literal list}$ **and**
 $S :: 'v \text{ twl-state}$
defines
 $xs \equiv [L \leftarrow \text{remdups } C . - L \notin \text{lits-of-l (raw-trail } S)]$ **and**
 $ys \equiv [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) \text{ (raw-trail } S) . L \in \text{set } C]$
assumes
 $n\text{-d: no-dup (raw-trail } S)$ **and**
 $Nil\text{-Nil: } xs = [] \implies ys = [] \implies P$ **and**
 $Nil\text{-single:}$
 $\bigwedge a. xs = [] \implies ys = [a] \implies a \in \text{set } C \implies P$ **and**
 $Nil\text{-other: } \bigwedge a \ b \ ys'. xs = [] \implies ys = a \# b \# ys' \implies a \neq b \implies P$ **and**
 $single\text{-Nil: } \bigwedge a. xs = [a] \implies ys = [] \implies P$ **and**
 $single\text{-other: } \bigwedge a \ b \ ys'. xs = [a] \implies ys = b \# ys' \implies a \neq b \implies P$ **and**
 $other: \bigwedge a \ b \ xs'. xs = a \# b \# xs' \implies a \neq b \implies P$
shows P
using $watch\text{-nat-list-cases-witness}[OF \ n\text{-d, of } C \ P]$
 $Nil\text{-Nil } Nil\text{-single } Nil\text{-other } single\text{-Nil } single\text{-other } other$

unfolding $xs\text{-def}[symmetric]$ $ys\text{-def}[symmetric]$ **by** *auto*

lemma *watch-nat-lists-set-union-witness*:
fixes
 $C :: 'v \text{ literal list}$ **and**
 $S :: 'v \text{ twl-state}$
defines
 $xs \equiv [L \leftarrow \text{remdups } C. - L \notin \text{lits-of-l (raw-trail } S)]$ **and**
 $ys \equiv [L \leftarrow \text{map } (\lambda L. - \text{lit-of } L) (\text{raw-trail } S) . L \in \text{set } C]$
assumes $n\text{-d: no-dup (raw-trail } S)$
shows $\text{set } C = \text{set } xs \cup \text{set } ys$
using $n\text{-d}$ **unfolding** $xs\text{-def}$ $ys\text{-def}$ **by** (*auto simp: lits-of-def comp-def uminus-lit-swap*)

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 $\text{no-dup (raw-trail } S)$
shows $\text{clause (watch-nat } S \ C) = \text{mset } C$
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 multiset-eq-iff raw-clause-def clause-def*)

lemma *index-uminus-index-map-uminus*:
 $-a \in \text{set } L \implies \text{index } L \ (-a) = \text{index (map uminus } L) \ (a::'a \text{ literal})$
by (*induction L*) *auto*

lemma *index-filter*:
 $a \in \text{set } L \implies b \in \text{set } L \implies P \ a \implies P \ b \implies$
 $\text{index } L \ a \leq \text{index } L \ b \longleftrightarrow \text{index (filter } P \ L) \ a \leq \text{index (filter } P \ L) \ b$
by (*induction L*) *auto*

lemma *foldr-remove1-W-Nil[simp]*: $\text{foldr remove1 } W \ [] = []$
by (*induct W*) *auto*

lemma *image-lit-of-mmset-of-mlit[simp]*:
 $\text{lit-of ' mmset-of-mlit ' } A = \text{lit-of ' } A$
unfolding *comp-def*
using $[[\text{simp-trace}]]$ **by** (*simp add: image-image comp-def*)

lemma *distinct-filter-eq*:
assumes $\text{distinct } xs$
shows $[L \leftarrow xs. L = a] = (\text{if } a \in \text{set } xs \text{ then } [a] \text{ else } [])$
using *assms* **by** (*induction xs*) *auto*

lemma *no-dup-distinct-map-uminus-lit-of*:
 $\text{no-dup } xs \implies \text{distinct (map } (\lambda L. - \text{lit-of } L) \ xs)$
by (*induction xs*) *auto*

lemma *wf-watch-witness*:
fixes $C :: 'v \text{ literal list}$ **and**
 $S :: 'v \text{ twl-state}$
defines

```

    ass: neg-not-assigned  $\equiv$  filter ( $\lambda L. -L \notin \text{ lits-of-l } (\text{raw-trail } S)$ ) (remdups C) and
    tr: neg-assigned-sorted-by-trail  $\equiv$  filter ( $\lambda L. L \in \text{ set } C$ ) (map ( $\lambda L. -\text{lit-of } L$ ) (raw-trail S))
defines
    W: W  $\equiv$  take 2 (neg-not-assigned @ neg-assigned-sorted-by-trail)
assumes
    n-d[simp]: no-dup (raw-trail S)
shows wf-twl-cls (raw-trail S) (TWL-Clause W (foldr remove1 W C))
unfolding wf-twl-cls.simps struct-wf-twl-cls.simps
proof (intro conjI, goal-cases)
  case 1
  then show ?case using n-d W unfolding ass tr
    apply (cases rule: watch-nat-list-cases-witness[of S C, OF n-d])
    by (auto simp: distinct-mset-add-single)
next
  case 2
  then show ?case unfolding W by simp
next
  case 3
  show ?case using n-d
    proof (cases rule: watch-nat-list-cases-witness[of S C])
      case Nil-Nil
      then have set C = set []  $\cup$  set []
        using watch-nat-lists-set-union-witness n-d by metis
      then show ?thesis
        by simp
    next
      case (Nil-single a)
      moreover have  $\bigwedge x. \text{ set } C = \{a\} \implies - a \in \text{ lits-of-l } (\text{trail } S) \implies x \in \text{ set } (\text{remove1 } a \text{ } C) \implies$ 
         $x = a$ 
        using notin-set-remove1 by auto
      ultimately show ?thesis
        using watch-nat-lists-set-union-witness[of S C] 3 by (auto simp: W ass tr comp-def)
    next
      case Nil-other
      then show ?thesis
        using 3 by (auto simp: W ass tr)
    next
      case (single-Nil a)
      show ?thesis
        using watch-nat-lists-set-union-witness[of S C] 3
        by (fastforce simp add: W ass tr single-Nil comp-def distinct-filter-eq
          no-dup-distinct-map-uminus-lit-of min-def)
    next
      case single-other
      then show ?thesis
        using 3 by (auto simp: W ass tr)
    next
      case other
      then show ?thesis
        using 3 by (auto simp: W ass tr)
    qed
next
  case 4 note -[simp] = this
  show ?case
    using n-d apply (cases rule: watch-nat-list-cases-witness[of S C])
    apply (auto dest: filter-in-list-prop-verifiedD)

```

```

      simp: W ass tr lits-of-def filter-empty-conv)[4]
    using watch-nat-lists-set-union-witness[of S C]
  by (force dest: filter-in-list-prop-verifiedD simp: W ass tr lits-of-def)+
next
case 5
from n-d show ?case
proof (cases rule: watch-nat-list-cases-witness[of S 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] tr by (fastforce simp: W ass)
next
case Nil-other
then show ?thesis
  unfolding watched-only-lazy-updates.simps Ball-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 - -  $\lambda L. L \in \text{set } C$ ])
  by (auto dest: filter-in-list-prop-verifiedD
    simp: uminus-lit-swap lits-of-def o-def W ass tr dest: in-diffD)
next
case single-Nil
then show ?thesis
  using watch-nat-lists-set-union-witness[of S C] tr by (fastforce simp: W ass)
next
case single-other
then show ?thesis
  unfolding watched-only-lazy-updates.simps Ball-def
  apply (clarify)
  apply (subst index-uminus-index-map-uminus,
    simp add: index-uminus-index-map-uminus lits-of-def image-image 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 - -  $\lambda L. L \in \text{set } C$ ])
  by (auto dest: filter-in-list-prop-verifiedD
    simp: W ass tr uminus-lit-swap lits-of-def o-def dest: in-diffD)
next
case other
then show ?thesis
  unfolding watched-only-lazy-updates.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 - -  $\lambda L. L \in \text{set } C$ ])
  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 (raw-trail S)  $\implies$  wf-twl-cls (raw-trail S) (watch-nat S C)
  using wf-watch-witness[of S C] watch-nat-def by metis

definition
  rewatch-nat ::
    'v literal  $\Rightarrow$  'v twl-state  $\Rightarrow$  'v twl-clause  $\Rightarrow$  'v twl-clause
where
  rewatch-nat L S C =
    (if  $-L \in \text{set } (\text{watched } C)$  then
      case filter ( $\lambda L'. L' \notin \text{set } (\text{watched } C) \wedge -L' \notin \text{insert } L (\text{lits-of-l } (\text{trail } S))$ )
        (unwatched C) of
        []  $\Rightarrow$  C
      | L' # -  $\Rightarrow$ 
        TWL-Clause (L' # remove1 (-L) (watched C)) (-L # remove1 L' (unwatched C))
    else
      C)

lemma clause-rewatch-nat:
  fixes UW :: 'v literal list and
    S :: 'v twl-state and
    L :: 'v literal and C :: 'v twl-clause
  shows clause (rewatch-nat L S C) = clause C
  using List.set-remove1-subset[of -L watched C]
  apply (cases C)
  by (auto simp: raw-clause-def rewatch-nat-def ac-simps multiset-eq-iff clause-def
    split: list.split
    dest: filter-in-list-prop-verifiedD)

lemma filter-sorted-list-of-multiset-Nil:
   $[x \leftarrow \text{sorted-list-of-multiset } M. p \ x] = [] \iff (\forall x \in \# M. \neg p \ x)$ 
  by auto (metis empty-iff filter-set list.set(1) member-filter set-sorted-list-of-multiset)

lemma filter-sorted-list-of-multiset-ConsD:
   $[x \leftarrow \text{sorted-list-of-multiset } M. p \ x] = x \# xs \implies p \ x$ 
  by (metis filter-set insert-iff list.set(2) member-filter)

lemma mset-minus-single-eq-empty:
   $a - \{\#b\# \} = \{\#\} \iff a = \{\#b\# \} \vee a = \{\#\}$ 
  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  $\leq$  2
  shows  $W = \{\#\} \vee (\exists a. W = \{\#a\# \}) \vee (\exists a \ b. W = \{\#a, b\# \})$ 
proof -
  have size W = 0  $\vee$  size W = 1  $\vee$  size W = 2
  using assms by linarith
  then show ?thesis
  using assms by (fastforce elim!: size-mset-SucE simp: Num.numeral-2-eq-2)
qed

lemma filter-sorted-list-of-multiset-eqD:

```



```

assumes  $[x \leftarrow \text{sorted-list-of-multiset } A. p \ x] = x \# \text{xs}$  (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':
assumes
  wf: wf-twl-cls (raw-trail S) C and
  undef: undefined-lit (raw-trail S) (lit-of L)
shows wf-twl-cls (L # raw-trail S) (rewatch-nat (lit-of L) S C)
proof (cases - lit-of L  $\in$  set (watched C))
  case False
  then show ?thesis
    apply (cases C)
    using wf undef unfolding rewatch-nat-def
    by (auto simp: uminus-lit-swap Decided-Propagated-in-iff-in-lits-of-l comp-def)
next
  case falsified: True

  let ?unwatched-nonfalsified =
     $[L' \leftarrow \text{unwatched } C. L' \notin \text{set } (\text{watched } C) \wedge - L' \notin \text{insert } (\text{lit-of } L) (\text{lits-of-l } (\text{trail } S))]$ 
  obtain W UW where C: C = TWL-Clause W UW
    by (cases C)

  show ?thesis
  proof (cases ?unwatched-nonfalsified)
    case Nil
    show ?thesis
      using falsified Nil
      apply (simp only: wf-twl-cls.simps if-True list.cases C rewatch-nat-def
        struct-wf-twl-cls.simps)
      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  $\bigwedge p \ l. \text{filter } p (\text{unwatched } C) \neq [] \vee l \notin \text{set } UW \vee \neg p \ l$ 
          unfolding C by (metis (no-types) filter-empty-conv twl-clause.sel(2))
        then show ?case
          using 4(2) C by auto
      next
        case 5
        then show ?case

```

```

    using wf by (fastforce simp add: C comp-def uminus-lit-swap)
qed
next
case (Cons L' Ls)
show ?thesis
  unfolding rewatch-nat-def
  using falsified Cons
  apply (simp only: wf-tw-clcls.simps if-True list.cases C struct-wf-tw-clcls.simps)
  apply (intro conjI)
  proof goal-cases
    case 1
    have distinct (watched (TWL-Clause W UW))
      using wf unfolding C by auto
    moreover have  $L' \notin \text{set } (\text{remove1 } (-\text{lit-of } L) (\text{watched } (TWL-Clause W UW)))$ 
      using 1(2) not-gr0 by (fastforce dest: filter-in-list-prop-verifiedD in-diffD)
    ultimately show ?case
      by (auto simp: distinct-mset-single-add)
  next
    case 2
    have f2:  $[l \leftarrow \text{unwatched } (TWL-Clause W UW) . l \notin \text{set } (\text{watched } (TWL-Clause W UW)) \wedge -l \notin \text{insert } (\text{lit-of } L) (\text{lits-of-l } (\text{trail } S))] \neq []$ 
      using 2(2) by simp
    then have  $\neg \text{set } UW \subseteq \text{set } W$ 
      using 2 by (auto simp add: filter-empty-conv)
    then show ?case
      using wf C 2(1) by (auto simp: length-remove1)
  next
    case 3
    have  $W: \text{length } W \leq \text{Suc } 0 \longleftrightarrow \text{length } W = 0 \vee \text{length } W = \text{Suc } 0$ 
      by linarith
    show ?case
      using wf C 3 by (auto simp: length-remove1 W length-list-Suc-0 dest!: subset-singletonD)
  next
    case 4
    have  $H: \forall L \in \text{set } W. -L \in \text{lits-of-l } (\text{trail } S) \longrightarrow (\forall L' \in \text{set } UW. L' \notin \text{set } W \longrightarrow -L' \in \text{lits-of-l } (\text{trail } S))$ 
      using wf by (auto simp: C)
    have  $W: \text{length } W \leq 2$  and  $W-UW: \text{length } W < 2 \longrightarrow \text{set } UW \subseteq \text{set } W$ 
      using wf by (auto simp: C)
    have distinct: distinct W
      using wf by (auto simp: C)
    show ?case
      using 4
      unfolding C watched-only-lazy-updates.simps Ball-def twl-clause.sel
        watched-wf-tw-clcls.simps
      apply (intro allI impI)
      apply (rename-tac xW xUW)
      apply (case-tac - lit-of L = xW; case-tac xW = xUW; case-tac L' = xW)
        apply (auto simp: uminus-lit-swap)[2]
        apply (force dest: filter-in-list-prop-verifiedD)
      using H distinct apply (fastforce)
      using distinct apply (fastforce)
      using distinct apply (fastforce)
      apply (force dest: filter-in-list-prop-verifiedD)
      using H by (auto simp: uminus-lit-swap)
  next

```

```

case 5
have H:  $\forall x. x \in \text{set } W \longrightarrow \neg x \in \text{lits-of-l } (\text{trail } S) \longrightarrow (\forall x. x \in \text{set } UW \longrightarrow x \notin \text{set } W \longrightarrow \neg x \in \text{lits-of-l } (\text{trail } S))$ 
  using wf by (auto simp: C)
show ?case
  unfolding C watched-only-lazy-updates.simps Ball-def
  proof (intro allI impI conjI, goal-cases)
    case (1 xW x)
    show ?case
      proof (cases  $\neg \text{lit-of } L = xW$ )
        case True
        then show ?thesis
          by (cases  $xW = x$ ) (auto simp: uminus-lit-swap)
      next
        case False note LxW = this
        have f9:  $L' \in \text{set } [l \leftarrow \text{unwatched } C. l \notin \text{set } (\text{watched } (TWL\text{-Clause } W UW)) \wedge \neg l \in \text{lits-of-l } (L \# \text{raw-trail } S)]$ 
          using 1(2) 5 C by auto
        moreover then have f11:  $\neg xW \in \text{lits-of-l } (\text{trail } S)$ 
          using 1(3) LxW by (auto simp: uminus-lit-swap)
        moreover then have xW  $\notin \text{set } W$ 
          using f9 1(2) H by (auto simp: C)
        ultimately have False
          using 1 by auto
        then show ?thesis
          by fast
      qed
    qed
  qed
qed

```

```

interpretation twl: abstract-tw1 watch-nat rewatch-nat raw-learned-clss
  apply unfold-locales
  apply (rule clause-watch-nat; simp add: image-image comp-def)
  apply (rule wf-watch-nat; simp add: image-image comp-def)
  apply (rule clause-rewatch-nat)
  apply (rule clause-rewatch-witness'; simp add: image-image comp-def)
  apply (simp)
done

```

```

interpretation twl2: abstract-tw1 watch-nat rewatch-nat  $\lambda\cdot$ . []
  apply unfold-locales
  apply (rule clause-watch-nat; simp add: image-image comp-def)
  apply (rule wf-watch-nat; simp add: image-image comp-def)
  apply (rule clause-rewatch-nat)
  apply (rule clause-rewatch-witness'; simp add: image-image comp-def)
  apply (simp)
done

```

```

end

```

7.3.2 Two Watched-Literals with invariant

```
theory CDCL-Two-Watched-Literals-Invariant
imports CDCL-Two-Watched-Literals DPLL-CDCL-W-Implementation
begin
```

Interpretation for *conflict-driven-clause-learning_W.cdcl_W*

We define here the 2-WL with the invariant of well-foundedness and show the role of the candidates by defining an equivalent CDCL procedure using the candidates given by the data-structure.

```
context abstract-twl
begin
```

Direct Interpretation lemma *mset-map-removeAll-cond:*

```
mset (map clause
      (removeAll-cond (λD. clause D = clause C) N))
= mset (removeAll (clause C) (map clause N))
by (induction N) auto
```

lemma *raw-clss-l-raw-init-clss-conc-init-clss[simp]:*

```
raw-clss-l (raw-init-clss S) = twl.conc-init-clss S
by (cases S) auto
```

lemma *mset-raw-init-clss-init-state:*

```
raw-clss-l (raw-init-clss (init-state (map raw-clause N))) = raw-clss-l N
unfolding raw-clss-l-raw-init-clss-conc-init-clss
by (metis (full-types) clause-def comp-def init-clss-init-state map-eq-conv map-map)
```

fun *reduce-trail-to where*

```
reduce-trail-to M1 S =
  (case S of
    (TWL-State M N U k C) ⇒ TWL-State (drop (length M - length M1) M) N U k C)
```

abbreviation *resolve-conflicting where*

```
resolve-conflicting L D S ≡
  update-conflicting
  (Some (union-mset-list (remove1 (-L) (the (raw-conflicting S))) (remove1 L (raw-clause D))))
  S
```

interpretation *rough-cdcl: abs-state_W-ops*

```
clause
raw-clss-l
λL C. L ∈ set C op #
```

```
mset
```

```
raw-clause λC. TWL-Clause [] C
trail λS. hd (raw-trail S)
(λS. raw-init-clss S @ raw-learned-clss S) backtrack-lvl raw-conflicting
conc-learned-clss
```

```
cons-trail tl-trail λS. update-conflicting None (add-learned-cls (the (raw-conflicting S)) S)
λC. remove-cls (raw-clause C)
update-backtrack-lvl
λC. update-conflicting (Some C) reduce-trail-to resolve-conflicting
```

```

     $\lambda N. \text{init-state } (\text{map raw-clause } N) \text{ restart'}$ 
rewrites
     $\text{rough-cdcl.mmset-of-mlit} = \text{mmset-of-mlit}$ 
proof goal-cases
  case 1
  show  $H$ : ?case by unfold-locales

  case 2
  show ?case
    apply (rule ext)
    apply (rename-tac x)
    apply (case-tac x)
    apply (simp-all add: abs-stateW-ops.mmset-of-mlit.simps[OF H] raw-clause-def clause-def)
  done
qed

interpretation rough-cdcl: abs-stateW
  clause
  raw-clss-l
   $\lambda L C. L \in \text{set } C \text{ op } \#$ 

  mset

  raw-clause  $\lambda C. \text{TWL-Clause } [] C$ 
  trail  $\lambda S. \text{hd } (\text{raw-trail } S)$ 
  ( $\lambda S. \text{raw-init-clss } S @ \text{raw-learned-clss } S$ ) backtrack-lvl raw-conflicting
  conc-learned-clss

  cons-trail tl-trail  $\lambda S. \text{update-conflicting None } (\text{add-learned-clss } (\text{the } (\text{raw-conflicting } S)) S)$ 
   $\lambda C. \text{remove-clss } (\text{raw-clause } C)$ 
  update-backtrack-lvl
   $\lambda C. \text{update-conflicting } (\text{Some } C) \text{ reduce-trail-to resolve-conflicting}$ 
   $\lambda N. \text{init-state } (\text{map raw-clause } N) \text{ restart'}$ 
proof goal-cases
  case 1
  have stupid-locales: abs-stateW-ops clause raw-clss-l ( $\lambda L C. L \in \text{set } C$ ) op  $\#$ 
    mset raw-clause (TWL-Clause  $[]$ )
    by unfold-locales
  have [simp]: abs-stateW-ops.mmset-of-mlit clause = mmset-of-mlit
    apply (rule ext, rename-tac L, case-tac L)
    by (auto simp: abs-stateW-ops.mmset-of-mlit.simps[OF stupid-locales] clause-def raw-clause-def)
  have [simp]:  $\bigwedge S. \text{raw-clss-l } (\text{restart-learned } S) \subseteq \# \text{conc-learned-clss } S$ 
    using image-mset-subseteq-mono[OF restart-learned] unfolding mset-map
    by blast
  have [simp]:  $\bigwedge st C. \text{mset } (\text{removeAll } (\text{clause } C) (\text{map clause } (\text{raw-init-clss } st))) =$ 
     $\text{removeAll-mset } (\text{clause } C) (\text{rough-cdcl.conc-init-clss } st)$ 
    unfolding rough-cdcl.conc-init-clss-def by (metis mset-removeAll rough-cdcl.conc-init-clss-def twl2.raw-clss-l-raw-init-clss-conc-init-clss)

  have  $H$ :  $\bigwedge M2 M1 x1. M2 @ M1 = \text{map mmset-of-mlit } x1 \implies$ 
     $\text{map mmset-of-mlit } (\text{drop } (\text{length } x1 - \text{length } M1) x1) = M1$ 
    by (metis add-diff-cancel-right' append-eq-conv-conj drop-map length-append length-map)
  show  $H$ : ?case
    apply unfold-locales
    apply (case-tac raw-trail S; case-tac hd (raw-trail S))

```

by (auto simp add: add-init-cls-def add-learned-cls-def clause-rewatch clause-watch
 cons-trail-def remove-cls-def restart'-def tl-trail-def map-tl comp-def
 ac-simps mset-map-removeAll-cond mset-raw-init-clss-init-state rough-cdcl.state-def
 clause-def[symmetric] H union-mset-list[symmetric] split: twl-state.splits)
 qed

interpretation rough-cdcl: abs-conflict-driven-clause-learning_w

clause

raw-clss-l

$\lambda L C. L \in \text{set } C \text{ op } \#$

mset

raw-clause $\lambda C. \text{TWL-Clause } [] C$

trail $\lambda S. \text{hd } (\text{raw-trail } S)$

$(\lambda S. \text{raw-init-clss } S @ \text{raw-learned-clss } S) \text{ backtrack-lvl raw-conflicting}$

conc-learned-clss

cons-trail tl-trail $\lambda S. \text{update-conflicting None (add-learned-cls (the (raw-conflicting } S)) S)$

$\lambda C. \text{remove-cls (raw-clause } C)$

update-backtrack-lvl

$\lambda C. \text{update-conflicting (Some } C) \text{ reduce-trail-to resolve-conflicting}$

$\lambda N. \text{init-state (map raw-clause } N) \text{ restart}'$

by unfold-locales

declare local.rough-cdcl.mset-ccls-ccls-of-cls[simp del]

Opaque Type with Invariant **declare** rough-cdcl.state-simp[simp del]

definition cons-trail-twl :: ('v, 'v twl-clause) ann-lit \Rightarrow 'v wf-twl \Rightarrow 'v wf-twl

where

cons-trail-twl L S \equiv twl-of-rough-state (cons-trail L (rough-state-of-twl S))

lemma wf-twl-state-cons-trail:

assumes

undef: undefined-lit (raw-trail S) (lit-of L) **and**

wf: wf-twl-state S

shows wf-twl-state (cons-trail L S)

using undef wf wf-rewatch[of S] **unfolding** wf-twl-state-def Ball-def

by (auto simp: cons-trail-def defined-lit-map comp-def image-def

rough-cdcl.conc-clauses-init-learned)

lemma rough-state-of-twl-cons-trail:

undefined-lit (raw-trail-twl S) (lit-of L) \implies

rough-state-of-twl (cons-trail-twl L S) = cons-trail L (rough-state-of-twl S)

using rough-state-of-twl twl-of-rough-state-inverse wf-twl-state-cons-trail

unfolding cons-trail-twl-def **by** blast

abbreviation add-init-cls-twl **where**

add-init-cls-twl C S \equiv twl-of-rough-state (add-init-cls C (rough-state-of-twl S))

lemma wf-twl-add-init-cls: wf-twl-state S \implies wf-twl-state (add-init-cls L S)

unfolding wf-twl-state-def **by** (auto simp: wf-watch add-init-cls-def comp-def

rough-cdcl.conc-clauses-init-learned

split: if-split-asm)

lemma *rough-state-of-twl-add-init-cls*:
 $\text{rough-state-of-twl } (\text{add-init-cls-twl } L \ S) = \text{add-init-cls } L \ (\text{rough-state-of-twl } S)$
using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-add-init-cls* **by** *blast*

abbreviation *add-learned-cls-twl* **where**
 $\text{add-learned-cls-twl } C \ S \equiv \text{twl-of-rough-state } (\text{add-learned-cls } C \ (\text{rough-state-of-twl } S))$

lemma *wf-twl-add-learned-cls*: $\text{wf-twl-state } S \implies \text{wf-twl-state } (\text{add-learned-cls } L \ S)$
unfolding *wf-twl-state-def* **by** (*auto simp*: *wf-watch add-learned-cls-def*
rough-cdcl.conc-clauses-init-learned
split: *if-split-asm*)

lemma *rough-state-of-twl-add-learned-cls*:
 $\text{rough-state-of-twl } (\text{add-learned-cls-twl } L \ S) = \text{add-learned-cls } L \ (\text{rough-state-of-twl } S)$
using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-add-learned-cls* **by** *blast*

abbreviation *remove-cls-twl* **where**
 $\text{remove-cls-twl } C \ S \equiv \text{twl-of-rough-state } (\text{remove-cls } C \ (\text{rough-state-of-twl } S))$

lemma *set-removeAll-condD*: $x \in \text{set } (\text{removeAll-cond } f \ xs) \implies x \in \text{set } xs$
by (*induction xs*) (*auto split*: *if-split-asm*)

lemma *wf-twl-remove-cls*: $\text{wf-twl-state } S \implies \text{wf-twl-state } (\text{remove-cls } L \ S)$
unfolding *wf-twl-state-def* **by** (*auto simp*: *wf-watch remove-cls-def*
comp-def split: *if-split-asm dest*: *set-removeAll-condD*)

lemma *rough-state-of-twl-remove-cls*:
 $\text{rough-state-of-twl } (\text{remove-cls-twl } L \ S) = \text{remove-cls } L \ (\text{rough-state-of-twl } S)$
using *rough-state-of-twl twl-of-rough-state-inverse wf-twl-remove-cls* **by** *blast*

abbreviation *init-state-twl* **where**
 $\text{init-state-twl } N \equiv \text{twl-of-rough-state } (\text{init-state } N)$

lemma *wf-twl-state-wf-twl-state-fold-add-init-cls*:
assumes *wf-twl-state S*
shows *wf-twl-state (fold add-init-cls N S)*
using *assms apply* (*induction N arbitrary*: *S*)
apply (*auto simp*: *wf-twl-state-def*)
by (*simp add*: *wf-twl-add-init-cls*)

lemma *wf-twl-state-epsilon-state[simp]*:
 $\text{wf-twl-state } (\text{TWL-State } [] \ [] \ 0 \ \text{None})$
by (*auto simp*: *wf-twl-state-def*)

lemma *wf-twl-init-state*: $\text{wf-twl-state } (\text{init-state } N)$
unfolding *init-state-def* **by** (*auto intro*!: *wf-twl-state-wf-twl-state-fold-add-init-cls*)

lemma *rough-state-of-twl-init-state*:
 $\text{rough-state-of-twl } (\text{init-state-twl } N) = \text{init-state } N$
by (*simp add*: *twl-of-rough-state-inverse wf-twl-init-state*)

abbreviation *tl-trail-twl* **where**
 $\text{tl-trail-twl } S \equiv \text{twl-of-rough-state } (\text{tl-trail } (\text{rough-state-of-twl } S))$

lemma *wf-twl-state-tl-trail*: $\text{wf-twl-state } S \implies \text{wf-twl-state } (\text{tl-trail } S)$
by (*auto 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 comp-def)

lemma *rough-state-of-twl-tl-trail:*

rough-state-of-twl (tl-trail-twl S) = tl-trail (rough-state-of-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-backtrack-lvl-twl k S ≡ twl-of-rough-state (update-backtrack-lvl k (rough-state-of-twl S))

lemma *wf-twl-state-update-backtrack-lvl:*

wf-twl-state S ⇒ wf-twl-state (update-backtrack-lvl k S)

unfolding *wf-twl-state-def* **by** *(auto simp: comp-def)*

lemma *rough-state-of-twl-update-backtrack-lvl:*

rough-state-of-twl (update-backtrack-lvl-twl k S) = update-backtrack-lvl k (rough-state-of-twl S)

using *rough-state-of-twl*

twl-of-rough-state-inverse[of update-backtrack-lvl k (rough-state-of-twl S)]

wf-twl-state-update-backtrack-lvl[of rough-state-of-twl S k] **by** *fast*

abbreviation *update-conflicting-twl* **where**

update-conflicting-twl k S ≡ twl-of-rough-state (update-conflicting k (rough-state-of-twl S))

lemma *wf-twl-state-update-conflicting:*

wf-twl-state S ⇒ wf-twl-state (update-conflicting k S)

unfolding *wf-twl-state-def* **by** *(auto simp: comp-def)*

lemma *rough-state-of-twl-update-add-learned-cl:*

rough-state-of-twl (update-conflicting-twl None (add-learned-cl-twl C S)) = update-conflicting None (add-learned-cl C (rough-state-of-twl S))

(is rough-state-of-twl ?upd = update-conflicting None ?le)

using *rough-state-of-twl[of ?upd] twl-of-rough-state-inverse*

wf-twl-add-learned-cl[of rough-state-of-twl S C]

wf-twl-state-update-conflicting[of ?le None]

by *fastforce*

abbreviation *reduce-trail-to-twl* **where**

reduce-trail-to-twl M1 S ≡ twl-of-rough-state (reduce-trail-to M1 (rough-state-of-twl S))

abbreviation *resolve-conflicting-twl* **where**

resolve-conflicting-twl L D S ≡

twl-of-rough-state (resolve-conflicting L D (rough-state-of-twl S))

lemma *rough-state-of-twl-update-conflicting:*

rough-state-of-twl (update-conflicting-twl k S) = update-conflicting k (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**

raw-clauses-twl S ≡ raw-clauses (rough-state-of-twl S)

abbreviation *restart-twl* **where**

restart-twl S ≡ twl-of-rough-state (restart' (rough-state-of-twl S))

lemma *mset-union-mset-setD:*

mset A ⊆# mset B ⇒ set A ⊆ set B

by *auto*

lemma *wf-wf-restart'*: *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* (*raw-trail* S) x)
apply (*case-tac* x)
using *restart-learned* **by** (*auto simp: comp-def dest: mset-union-mset-setD*)

lemma *rough-state-of-twl-restart-twl*:
rough-state-of-twl (*restart-twl* S) = *restart'* (*rough-state-of-twl* S)
by (*simp add: twl-of-rough-state-inverse wf-wf-restart'*)

lemma *undefined-lit-trail-twl-raw-trail*[*iff*]:
undefined-lit (*trail-twl* S) $L \longleftrightarrow \text{undefined-lit } (\text{raw-trail-twl } S) L$
by (*auto simp: defined-lit-map image-image*)

lemma *wf-twl-reduce-trail-to*:
assumes *trail* $S = M2 @ M1$ **and** *wf*: *wf-twl-state* S
shows *wf-twl-state* (*reduce-trail-to* $M1 S$)
proof –
obtain $M N U k C$ **where** $S = \text{TWL-State } M N U k C$
by (*cases* S)
have *n-d*: *no-dup* M
using *wf* **by** (*auto simp: S comp-def wf-twl-state-def*)
have M : $M = \text{take } (\text{length } M - \text{length } M1) M @ \text{drop } (\text{length } M - \text{length } M1) M$
by *auto*
have [*simp*]: *no-dup* (*drop* (*length* $M - \text{length } M1$) M)
using *n-d* **by** (*metis distinct-drop drop-map*)
have $\bigwedge C. C \in \text{set } (\text{raw-clauses } S) \implies \text{wf-twl-cls } (\text{raw-trail } S) C$
using *wf* **by** (*auto simp: S comp-def wf-twl-state-def*)
then show *?thesis*
unfolding *wf-twl-state-def* S
using *wf-twl-cls-append*[*of* *take* (*length* $M - \text{length } M1$) M *drop* (*length* $M - \text{length } M1$) M ,
unfolded $M[\text{symmetric}]$]
by (*simp-all add: n-d*)
qed

lemma *trail-twl-twl-rough-state-reduce-trail-to*:
assumes *trail-twl* $st = M2 @ M1$
shows *trail-twl* (*twl-of-rough-state* (*reduce-trail-to* $M1$ (*rough-state-of-twl* st))) = $M1$
proof –
have *wf-twl-state* (*reduce-trail-to* $M1$ (*rough-state-of-twl* st))
using *wf-twl-reduce-trail-to* *assms* **by** *fastforce*
moreover
have *length* (*trail-twl* st) – *length* $M1$ = *length* $M2$
unfolding *assms* **by** *auto*
then have *trail* (*reduce-trail-to* $M1$ (*rough-state-of-twl* st)) = $M1$
apply (*cases* *rough-state-of-twl* st)
using *assms* **by** (*auto simp: drop-map[symmetric]*)
ultimately show *?thesis*
using *twl-of-rough-state-inverse*[*of* *reduce-trail-to* $M1$ (*rough-state-of-twl* st)]
rough-state-of-twl[*of* st]
by (*auto simp add: assms*)
qed

lemma *twl-of-rough-state-reduce-trail-to*:

assumes *trail-twl st = M2 @ M1 and*

S: rough-cdcl.state (rough-state-of-twl st) = (M, S)

shows

rough-cdcl.state

(rough-state-of-twl (twl-of-rough-state (reduce-trail-to M1 (rough-state-of-twl st)))) = (M1, S) (is ?st) and

raw-init-clss-twl (twl-of-rough-state (reduce-trail-to M1 (rough-state-of-twl st)))

= raw-init-clss-twl st (is ?A) and

raw-learned-clss-twl (twl-of-rough-state (reduce-trail-to M1 (rough-state-of-twl st)))

= raw-learned-clss-twl st (is ?B) and

backtrack-lvl-twl (twl-of-rough-state (reduce-trail-to M1 (rough-state-of-twl st)))

= backtrack-lvl-twl st (is ?C) and

rough-cdcl.conc-conflicting (rough-state-of-twl (twl-of-rough-state (reduce-trail-to M1 (rough-state-of-twl st))))

= rough-cdcl.conc-conflicting (rough-state-of-twl st) (is ?D)

proof –

have *wf-twl-state (reduce-trail-to M1 (rough-state-of-twl st))*

using *wf-twl-reduce-trail-to assms by fastforce*

moreover

have *length (trail-twl st) – length M1 = length M2*

unfolding *assms by auto*

then have

raw-init-clss (reduce-trail-to M1 (rough-state-of-twl st)) = raw-init-clss-twl st

raw-learned-clss (reduce-trail-to M1 (rough-state-of-twl st)) = raw-learned-clss-twl st

backtrack-lvl (reduce-trail-to M1 (rough-state-of-twl st)) = backtrack-lvl-twl st

rough-cdcl.conc-conflicting (reduce-trail-to M1 (rough-state-of-twl st)) =

rough-cdcl.conc-conflicting (rough-state-of-twl st)

using *assms by (cases rough-state-of-twl st, auto simp: drop-map[symmetric])+*

ultimately show *?A ?B ?C ?D*

using *twl-of-rough-state-inverse[of reduce-trail-to M1 (rough-state-of-twl st)]*

rough-state-of-twl[of st]

by *(auto simp add: assms)*

moreover have *trail-twl (twl-of-rough-state (reduce-trail-to M1 (rough-state-of-twl st))) = M1*

using *trail-twl-twl-rough-state-reduce-trail-to[OF assms(1)] .*

ultimately show *?st using S unfolding rough-cdcl.state-def*

by *(metis (no-types) prod.inject twl2.raw-clss-l-raw-init-clss-conc-init-clss)*

qed

lemma *add-learned-clss-rough-state-of-twl-simp*:

assumes *raw-conflicting-twl st = Some z*

shows

trail (add-learned-clss z (rough-state-of-twl st)) = trail-twl st

rough-cdcl.conc-init-clss (add-learned-clss z (rough-state-of-twl st)) =

rough-cdcl.conc-init-clss (rough-state-of-twl st)

conc-learned-clss (local.add-learned-clss z (rough-state-of-twl st)) =

{#mset z#} + conc-learned-clss (rough-state-of-twl st)

backtrack-lvl (add-learned-clss z (rough-state-of-twl st)) = backtrack-lvl-twl st

using *assms wf-twl-state-rough-state-of-twl[of st]*

unfolding *wf-twl-state-def apply*

(auto simp: wf-watch add-learned-clss-def comp-def local.clause-watch

ac-simps

split: if-split-asm)

done

sublocale *wf-twl*: *abs-state_W-ops*
clause
raw-clss-l
 $\lambda L\ C. L \in \text{set } C \text{ op } \#$

mset

 $\lambda C. \text{raw-clause } C\ \lambda C. \text{TWL-Clause } []\ C$
 $\text{trail-twl } \lambda S. \text{hd } (\text{raw-trail-twl } S)$
raw-clauses-twl
backtrack-lvl-twl
raw-conflicting-twl
conc-learned-clss-twl

cons-trail-twl
tl-trail-twl
 $\lambda S. \text{update-conflicting-twl } \text{None } (\text{add-learned-clss-twl } (\text{the } (\text{raw-conflicting-twl } S))\ S)$
 $\lambda C. \text{remove-clss-twl } (\text{raw-clause } C)$
update-backtrack-lvl-twl
 $\lambda C. \text{update-conflicting-twl } (\text{Some } C)$
reduce-trail-to-twl
resolve-conflicting-twl
 $\lambda N. \text{init-state-twl } (\text{map raw-clause } N)$
restart-twl
by *unfold-locales*

lemma *wf-twl-conc-init-clss-restart-twl[simp]*:
 $\text{wf-twl.conc-init-clss } (\text{restart-twl } S) = \text{wf-twl.conc-init-clss } S$
using *rough-state-of-twl-restart-twl wf-twl.conc-init-clss-def* **by** *auto*

sublocale *wf-twl*: *abs-state_W*
clause
raw-clss-l
 $\lambda L\ C. L \in \text{set } C \text{ op } \#$

mset

 $\lambda C. \text{raw-clause } C\ \lambda C. \text{TWL-Clause } []\ C$
 $\text{trail-twl } \lambda S. \text{hd } (\text{raw-trail-twl } S)$
raw-clauses-twl
backtrack-lvl-twl
raw-conflicting-twl
conc-learned-clss-twl

cons-trail-twl
tl-trail-twl
 $\lambda S. \text{update-conflicting-twl } \text{None } (\text{add-learned-clss-twl } (\text{the } (\text{raw-conflicting-twl } S))\ S)$
 $\lambda C. \text{remove-clss-twl } (\text{raw-clause } C)$
update-backtrack-lvl-twl
 $\lambda C. \text{update-conflicting-twl } (\text{Some } C)$
reduce-trail-to-twl
resolve-conflicting-twl
 $\lambda N. \text{init-state-twl } (\text{map raw-clause } N)$
restart-twl
proof *goal-cases*

```

case 1
have stupid-locales: abs-stateW-ops clause raw-clss-l ( $\lambda L C. L \in \text{set } C$ ) op #
  mset raw-clause (TWL-Clause [])
  by unfold-locales
have ugly[simp]: abs-stateW-ops.mmset-of-mlit clause = mmset-of-mlit
  apply (rule ext, rename-tac L, case-tac L)
  by (auto simp: abs-stateW-ops.mmset-of-mlit.simps[OF stupid-locales] clause-def
    raw-clause-def)
have [simp]:  $\bigwedge S. \text{raw-clss-l} (\text{restart-learned } S) \subseteq \# \text{conc-learned-clss } S$ 
  using image-mset-subseteq-mono[OF restart-learned] unfolding mset-map
  by blast
interpret abs-stateW-ops clause
  raw-clss-l
 $\lambda L C. L \in \text{set } C$  op #
  mset

 $\lambda C. \text{raw-clause } C \lambda C. \text{TWL-Clause } [] C$ 
  by unfold-locales
have abs:  $\bigwedge S. \text{abs-state}_W\text{-ops.state raw-clss-l mset trail-twl raw-clauses-twl}$ 
  backtrack-lvl-twl raw-conflicting-twl conc-learned-clss-twl  $S =$ 
  rough-cdcl.state (rough-state-of-twl  $S$ )
  using wf-twl.conc-init-clss-def unfolding abs-stateW-ops.state-def[OF stupid-locales] by auto
show ?case
  apply unfold-locales
    using rough-cdcl.hd-raw-conc-trail unfolding ugly apply blast
    apply (auto simp add: rough-state-of-twl-cons-trail rough-cdcl.state-def abs; fail)[]
    apply (auto simp add: rough-state-of-twl-tl-trail rough-cdcl.state-def abs; fail)[]
    apply (auto simp add: rough-state-of-twl-remove-cls
      rough-state-of-twl-update-backtrack-lvl rough-cdcl.state-def abs; fail)[]
    apply (auto simp add: rough-state-of-twl-update-add-learned-cls rough-cdcl.state-def
      add-learned-cls-rough-state-of-twl-simp
      abs; fail)[]
    apply (auto simp add: rough-state-of-twl-update-backtrack-lvl
      rough-state-of-twl-update-conflicting rough-cdcl.state-def abs; fail)[]
    apply (auto simp add: rough-state-of-twl-update-add-learned-cls rough-cdcl.state-def
      add-learned-cls-rough-state-of-twl-simp
      rough-state-of-twl-update-conflicting abs; fail)[]
    apply (auto simp add: rough-state-of-twl-update-add-learned-cls rough-cdcl.state-def
      rough-state-of-twl-update-conflicting abs; fail)[]
    using twl-of-rough-state-reduce-trail-to(1) unfolding abs
    using rough-cdcl.conc-init-clss-restart-state rough-cdcl.conc-learned-clss-restart-state
    apply (simp add: rough-cdcl.resolve-conflicting twl2.rough-state-of-twl-update-conflicting;
      fail)
  using twl-of-rough-state-reduce-trail-to(1) unfolding abs
  using rough-cdcl.conc-init-clss-restart-state rough-cdcl.conc-learned-clss-restart-state
  by (auto simp: rough-state-of-twl-restart-twl abs
    rough-cdcl.state-def rough-state-of-twl-init-state comp-def)[8]
qed

```

```

sublocale wf-twl: abs-conflict-driven-clause-learningW
  clause
  raw-clss-l
 $\lambda L C. L \in \text{set } C$  op #

  mset

```

$\lambda C. \text{raw-clause } C \ \lambda C. \text{TWL-Clause } [] \ C$
 $\text{trail-twl } \lambda S. \text{hd } (\text{raw-trail-twl } S)$
 raw-clauses-twl
 backtrack-lvl-twl
 $\text{raw-conflicting-twl}$
 $\text{conc-learned-clss-twl}$

 cons-trail-twl
 tl-trail-twl
 $\lambda S. \text{update-conflicting-twl } \text{None } (\text{add-learned-clss-twl } (\text{the } (\text{raw-conflicting-twl } S)) \ S)$
 $\lambda C. \text{remove-clss-twl } (\text{raw-clause } C)$
 $\text{update-backtrack-lvl-twl}$
 $\lambda C. \text{update-conflicting-twl } (\text{Some } C)$
 $\text{reduce-trail-to-twl}$
 $\text{resolve-conflicting-twl}$
 $\lambda N. \text{init-state-twl } (\text{map raw-clause } N)$
 restart-twl
by unfold-locales

declare $\text{local.rough-cdcl.mset-ccls-ccls-of-clss}[simp \ del]$
abbreviation $\text{state-eq-twl } (\text{infix } \sim \text{TWL } 51)$ **where**
 $\text{state-eq-twl } S \ S' \equiv \text{rough-cdcl.state-eq } (\text{rough-state-of-twl } S) \ (\text{rough-state-of-twl } S')$
notation $\text{wf-twl.state-eq } (\text{infix } \sim 51)$

To avoid ambiguities:

no-notation $\text{state-eq-twl } (\text{infix } \sim 51)$

Alternative Definition of CDCL using the candidates of 2-WL *inductive propagate-twl*

$:: 'v \text{wf-twl} \Rightarrow 'v \text{wf-twl} \Rightarrow \text{bool}$ **where**
 $\text{propagate-twl-rule}: (L, C) \in \text{candidates-propagate-twl } S \Rightarrow$
 $S' \sim \text{cons-trail-twl } (\text{Propagated } L \ C) \ S \Rightarrow$
 $\text{raw-conflicting-twl } S = \text{None} \Rightarrow$
 $\text{propagate-twl } S \ S'$

lemma $\text{cdcl}_W\text{-all-struct-inv-clause-distinct-mset}$:
 $\text{cdcl}_W\text{-mset.cdcl}_W\text{-all-struct-inv } (\text{wf-twl.state } S) \Rightarrow$
 $C \in \text{set } (\text{CDCL-Two-Watched-Literals.raw-clauses-twl } S) \Rightarrow \text{distinct } (\text{raw-clause } C)$
unfolding $\text{cdcl}_W\text{-mset.cdcl}_W\text{-all-struct-inv-def } \text{cdcl}_W\text{-mset.distinct-cdcl}_W\text{-state-def}$
 $\text{distinct-mset-set-def } \text{wf-twl.conc-clauses-init-learned}$
by $(\text{metis } (\text{no-types, lifting}) \text{distinct-mset-distinct-in-clss-mset-clss-union-iff}$
 $\text{wf-twl.conc-clauses-init-learned } \text{wf-twl.init-clss-state-conc-init-clss}$
 $\text{wf-twl.learned-clss-state-conc-learned-clss } \text{wf-twl.mset-ccls-ccls-of-clss})$

inductive-cases $\text{propagate-twlE}: \text{propagate-twl } S \ T$

lemma $\text{propagate-twl-iff-propagate}$:

assumes $\text{inv}: \text{cdcl}_W\text{-mset.cdcl}_W\text{-all-struct-inv } (\text{wf-twl.state } S)$
shows $\text{wf-twl.propagate-abs } S \ T \longleftrightarrow \text{propagate-twl } S \ T$ (**is** $?P \longleftrightarrow ?T$)

proof

assume $?P$

then obtain $L \ E$ **where**

$\text{raw-conflicting-twl } S = \text{None}$ **and**

$\text{CL-Clauses}: E \in \text{set } (\text{raw-clauses-twl } S)$ **and**

$\text{LE}: L \in \# \text{ clause } E$ **and**

$\text{tr-CNot}: \text{trail-twl } S \models_{\text{as}} \text{CNot } (\text{remove1-mset } L \ (\text{clause } E))$ **and**

$\text{undef-lot}[simp]: \text{undefined-lit } (\text{trail-twl } S) \ L$ **and**

```

   $T \sim \text{cons-trail-twl } (\text{Propagated } L \ E) \ S$ 
  by (blast elim: wf-twl.propagate-absE)
have distinct (raw-clause E)
  using inv CL-Clauses cdclW-all-struct-inv-clause-distinct-mset by blast
then have X: remove1-mset L (mset (raw-clause E)) = mset-set (set (raw-clause E) - {L})
  by (auto simp: multiset-eq-iff raw-clause-def count-mset distinct-filter-eq-if)
have (L, E) ∈ candidates-propagate-twl S
  apply (rule wf-candidates-propagate-complete)
    using rough-state-of-twl apply (auto; fail)[]
    using CL-Clauses apply (auto; fail)[]
    using LE apply (simp add: clause-def; fail)
    using tr-CNot X apply (simp add: clause-def; fail)
    using undef-lot apply blast
  done
show ?T
  apply (rule propagate-twl-rule)
    apply (rule ⟨(L, E) ∈ candidates-propagate-twl S⟩)
    using ⟨ $T \sim \text{cons-trail-twl } (\text{Propagated } L \ E) \ S$ ⟩
    apply (auto simp: ⟨raw-conflicting-twl S = None⟩ cdclW-mset.state-eq-def)
  done
next
assume ?T
then obtain L C where
  LC: (L, C) ∈ candidates-propagate-twl S and
  T:  $T \sim \text{cons-trail-twl } (\text{Propagated } L \ C) \ S$  and
  confl: raw-conflicting-twl S = None
  by (auto elim: propagate-twlE)
have
  C'S: C ∈ set (raw-clauses-twl S) and
  L: set (watched C) - uminus ' lits-of-l (trail-twl S) = {L} and
  undef: undefined-lit (trail-twl S) L
  using LC unfolding candidates-propagate-def by auto
have dist: distinct (raw-clause C)
  using inv C'S cdclW-all-struct-inv-clause-distinct-mset by blast
then have C-L-L: mset-set (set (raw-clause C) - {L}) = clause C - {#L#}
  by (metis distinct-mset-distinct distinct-mset-minus distinct-mset-set-mset-ident mset-remove1
    set-mset-mset set-remove1-eq clause-def)

show ?P
  apply (rule wf-twl.propagate-abs-rule[of S C L])
    using confl apply (auto; fail)[]
    using C'S apply (simp; fail)
    using L unfolding candidates-propagate-def
    apply (auto simp: raw-clause-def clause-def; fail)[]
    using wf-candidates-propagate-sound[OF - LC] rough-state-of-twl dist
    apply (simp add: distinct-mset-remove1-All true-annots-true-cls clause-def; fail)
    using undef apply (simp; fail)
  using T undef unfolding cdclW-mset.state-eq-def by auto
qed

no-notation twl.state-eq-twl (infix  $\sim$  TWL 51)

inductive conflict-twl where
  conflict-twl-rule:
   $C \in \text{candidates-conflict-twl } S \implies$ 
   $S' \sim \text{update-conflicting-twl } (\text{Some } (\text{raw-clause } C)) \ S \implies$ 

```

raw-conflicting-twl $S = \text{None} \implies$
conflict-twl $S S'$

inductive-cases *conflict-twlE*: *conflict-twl* $S T$

lemma *conflict-twl-iff-conflict*:

shows *wf-twl.conflict-abs* $S T \longleftrightarrow \text{conflict-twl } S T$ (**is** $?C \longleftrightarrow ?T$)

proof

assume $?C$

then obtain D **where**

S : *raw-conflicting-twl* $S = \text{None}$ **and**

D : $D \in \text{set } (\text{raw-clauses-twl } S)$ **and**

MD : *trail-twl* $S \models_{\text{as}} \text{CNot } (\text{clause } D)$ **and**

T : $T \sim \text{update-conflicting-twl } (\text{Some } (\text{raw-clause } D)) S$

by (*elim wf-twl.conflict-absE*)

have $D \in \text{candidates-conflict-twl } S$

apply (*rule wf-candidates-conflict-complete*)

apply *simp*

using D **apply** (*auto*; *fail*)[]

using MD S **by** *auto*

moreover have $T \sim \text{twl-of-rough-state } (\text{update-conflicting } (\text{Some } (\text{raw-clause } D)))$
(rough-state-of-twl $S)$)

using T **unfolding** *cdcl_W-mset.state-eq-def* **by** *auto*

ultimately show $?T$

using S **by** (*auto intro: conflict-twl-rule*)

next

assume $?T$

then obtain C **where**

C : $C \in \text{candidates-conflict-twl } S$ **and**

T : $T \sim \text{update-conflicting-twl } (\text{Some } (\text{raw-clause } C)) S$ **and**

confl: *raw-conflicting-twl* $S = \text{None}$

by (*auto elim: conflict-twlE*)

have

$C \in \text{set } (\text{raw-clauses-twl } S)$

using C **unfolding** *candidates-conflict-def* **by** *auto*

moreover have *trail-twl* $S \models_{\text{as}} \text{CNot } (\text{clause } C)$

using *wf-candidates-conflict-sound*[*OF* - C] **by** *auto*

ultimately show $?C$ **apply** –

apply (*rule wf-twl.conflict-abs-rule*[*of* - C])

using *confl* T **unfolding** *cdcl_W-mset.state-eq-def* **by** (*auto simp del: map-map*)

qed

We have shown that we we can use *conflict-twl* and *propagate-twl* in a CDCL calculus.

end

end