A First Complete Algorithm for Real Quantifier Elimination in Isabelle/HOL

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Abstract

We formalize a multivariate quantifier elimination (QE) algorithm in the theorem prover Isabelle/HOL. Our algorithm is complete, in that it is able to reduce *any* quantified formula in the first-order logic of real arithmetic to a logically equivalent quantifier-free formula. The algorithm we formalize is a hybrid mixture of Tarski's original QE algorithm [8] and the Ben-Or, Kozen, and Reif [2] algorithm, and it is the first complete multivariate QE algorithm formalized in Isabelle/HOL.

Remark

This is the AFP entry associated with a corresponding paper by Kosaian, Tan, and Platzer [6]. Various auxiliary sources [1, 7] beyond the original BKR paper were helpful in the development of this AFP entry. The most closely related works are by Cyril Cohen and Assia Mahboubi [4, 3, 5].

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theory *Multiv-Poly-Props*
imports
HOL−Computational-Algebra.Computational-Algebra
Polynomial-Interpolation.Ring-Hom-Poly
Virtual-Substitution.ExecutiblePolyProps
Sturm-Tarski.Pseudo-Remainder-Sequence

Factor-Algebraic-Polynomial.Poly-Connection
Virtual-Substitution.VSQuad

begin

1 Some definitions for lists of polynomials

abbreviation *lead-coeffs*:: *'a*::*zero Polynomial.poly list* ⇒ *'a list*
  where *lead-coeffs p-list* ≡ *map Polynomial.lead-coeff p-list*

definition *coeffs-list*:: *'a*::*zero Polynomial.poly list* ⇒ *'a list*
  where *coeffs-list p-list* ≡ *concat* (*map Polynomial.coeffs p-list*)

value *lead-coeffs* [[:((*Var 0* +(*Const* (*3*::*real*))∗((*Var 1*)^*2*)):: *real mpoly*), *0*, (*1*::*real mpoly*):]]

abbreviation *degrees*:: *'a*::*zero Polynomial.poly list* ⇒ *nat list*
  where *degrees polys* ≡ *map Polynomial.degree polys*

value *degrees* [[:((*Var 0* +(*Const* (*3*::*real*))∗((*Var 1*)^*2*)):: *real mpoly*), *0*, (*1*::*real mpoly*):]]

fun *variables*:: *real mpoly list* ⇒ *nat set*
  where *variables* [] = {}
  | *variables* (*h*#*T*) = (*vars h*) ∪ (*variables T*)

fun *variables-list*:: *real mpoly list* ⇒ *nat list*
  where *variables-list qs* = *sorted-list-of-set* (*variables qs*)

lemma *variables-prop*:
  shows *v* ∈ *variables qs* ⟷ (∃ *q* ∈ *set qs*. *v* ∈ *vars q*)
proof (*induct qs*)
  case *Nil*
  then show *?case* **by** *auto*
next
  case (*Cons a qs*)
  then show *?case* **by** *simp*
qed

lemma *variables-finite*:
  shows *finite* (*variables qs*)
proof (*induct qs*)
  case *Nil*
  then show *?case* **by** *auto*
next
  case (*Cons a qs*)
  then show *?case*
    by (*simp add*: *vars-finite*)
qed

lemma *variables-list-prop*:

shows $v \in set\ (variables\text{-}list\ qs) \longleftrightarrow (\exists\, q \in set\ qs.\ v \in vars\ q)$
using *variables-finite*
by (*simp add*: *variables-prop*)

2 Evaluating multivariate polynomials

definition *eval-mpoly*:: *real list* ⇒ *real mpoly* ⇒ *real*
where *eval-mpoly L p* = *insertion* (*nth-default 0 L*) *p*

value *eval-mpoly* [*4*, *1*, *2*] ((*Var 0* +(*Const* (*3*::*real*))∗((*Var 1*)^*2*)):: *real mpoly*)

definition *eval-mpoly-poly*:: *real list* ⇒ *real mpoly Polynomial.poly* ⇒ *real Polynomial.poly*
where *eval-mpoly-poly L p* = *map-poly* (*eval-mpoly L*) *p*

lemma *eval-mpoly-poly-coeff1*: *n* ≤ *Polynomial.degree* (*eval-mpoly-poly L p*) ⟹ *Polynomial.coeff* (*eval-mpoly-poly L p*) *n* = *eval-mpoly L* (*Polynomial.coeff p n*)
unfolding *eval-mpoly-poly-def*
by (*simp add*: *coeff-map-poly eval-mpoly-def*)

lemma *eval-mpoly-poly-coeff2*: ∀ *n* > *Polynomial.degree* (*eval-mpoly-poly L p*). *Polynomial.coeff* (*eval-mpoly-poly L p*) *n* = *0*
using *coeff-eq-0* **by** *auto*

value *eval-mpoly-poly* [*4*, *1*, *2*] [:((*Var 0* +(*Const* (*3*::*real*))∗((*Var 1*)^*2*)):: *real mpoly*), *0*, (*1*::*real mpoly*):]

definition *eval-mpoly-poly-list*:: *real list* ⇒ *real mpoly Polynomial.poly list* ⇒ *real Polynomial.poly list*
where *eval-mpoly-poly-list L p-list* = *map* (λ*x*. (*eval-mpoly-poly L x*)) *p-list*

interpretation *eval-mpoly-map-poly-comm-ring-hom*: *map-poly-comm-ring-hom eval-mpoly val*
apply (*unfold-locales*)
by (*auto simp add*: *eval-mpoly-def insertion-add insertion-mult*)

interpretation *eval-mpoly-map-poly-idom-hom*: *map-poly-idom-hom eval-mpoly val*..

interpretation *eval-mpoly-poly-comm-ring-hom*: *comm-ring-hom eval-mpoly-poly val*
apply *unfold-locales*
apply (*auto simp add*: *eval-mpoly-poly-def*)
using *eval-mpoly-map-poly-comm-ring-hom.base.map-poly-hom-add* **apply** *force*
using *eval-mpoly-map-poly-comm-ring-hom.hom-mult* **by** *auto*

interpretation *eval-mpoly-poly-map-poly-idom-hom*: *map-poly-idom-hom eval-mpoly-poly val*..

3 Removing highest degree monomial

definition *one-less-degree*:: *real mpoly Polynomial.poly* ⇒ *real mpoly Polynomial.poly*
where *one-less-degree p* = *p* − *Polynomial.monom* (*Polynomial.lead-coeff p*) (*Polynomial.degree p*)

lemma *one-less-degree-degree*:
assumes *Polynomial.degree p* > *0*
shows *Polynomial.degree*(*one-less-degree p*) < *Polynomial.degree p*
proof −
obtain *q* **where** *q*:*Polynomial.degree p* = *Suc q*
using *assms not0-implies-Suc* **by** *blast*
from *poly-as-sum-of-monoms*[*of p*]
have *p-is*: *p* = (∑ *i*≤*q*. *Polynomial.monom* (*poly.coeff p i*) *i*) + *Polynomial.monom* (*Polynomial.lead-coeff p*) (*Polynomial.degree p*)
by (*simp add*: *q*)
then have *e*: *p* − *Polynomial.monom* (*Polynomial.lead-coeff p*) (*Polynomial.degree p*) = (∑ *i*≤*q*. *Polynomial.monom* (*poly.coeff p i*) *i*)
using *diff-eq-eq* **by** *blast*
show *?thesis* **unfolding** *one-less-degree-def e*
by (*smt* (*z3*) *Polynomial.coeff-diff Polynomial.lead-coeff-monom Zero-not-Suc p-is cancel-comm-monoid-add-class.diff-cancel degree-0 degree-add-eq-left degree-monom-eq e leading-coeff-0-iff linorder-neqE-nat q*)
qed

lemma *sublist-prefix-property*:
assumes *length og-list* ≥ *length sub-list*
assumes ∀ *i* < *length sub-list*. *sub-list* ! *i* = *og-list* ! *i*
shows *Sublist.prefix sub-list og-list*
using *assms*
proof (*induct length sub-list arbitrary*: *sub-list*)
case *0*
then show *?case* **by** *auto*
next
case (*Suc x*)
then have ∃ *a l*. *sub-list* = *append l* [*a*]
by (*metis length-greater-0-conv rev-exhaust zero-less-Suc*)
then obtain *a l* **where** *al-prop*: *sub-list* = *append l* [*a*]
by *auto*
then have *length-l*: *List.length l* = *x*
using *Suc.hyps*(*2*) **by** *auto*
then have *prefix l og-list*
by (*metis Suc.hyps*(*1*) *Suc.hyps*(*2*) *Suc.prems*(*1*) *Suc.prems*(*2*) *Suc-leD al-prop butlast-snoc lessI nth-butlast order.strict-trans*)
then have ∃ *t*. *og-list* = *l* @ *t*
using *prefix-def* **by** *blast*
then obtain *t* **where** *t-prop*: *og-list* = *l* @ *t* **by** *auto*
then have *t-first*: *og-list* ! (*length sub-list* − *1*) = (*t* ! *0*)
by (*metis Suc.hyps*(*2*) *diff-Suc-1 diff-self-eq-0 length-l less-irrefl nth-append*)

```
  have sub-list ! (length sub-list − 1) = a
    using al-prop
    by fastforce
  then have og-list ! (length sub-list − 1) = a
    using Suc.hyps(2) Suc.prems by fastforce
  then have t-zero: t ! 0 = a
    using t-prop t-first by auto
  have length l = length sub-list − 1
    using Suc.hyps(2) length-l by presburger
  then have length t > 0
    using assms
   by (metis Suc.hyps(2) Suc.prems(1) append.right-neutral bot-nat-0.not-eq-extremum
diff-is-0-eq length-0-conv length-l lessI t-prop zero-less-diff)
  then have ∃ t1. t = a # t1
    using t-zero
    by (metis length-0-conv less-nat-zero-code list.exhaust nth-Cons-0)
  then show ?case
    using t-prop al-prop
    by force
qed

lemma one-less-degree-is-prefix:
  assumes Polynomial.degree q > 0
  shows Sublist.prefix (Polynomial.coeffs (one-less-degree q)) (Polynomial.coeffs q)
proof −
  let ?sub-list = Polynomial.coeffs (Multiv-Poly-Props.one-less-degree q)
   have ∀ i < length ?sub-list. Polynomial.coeff (one-less-degree q) i = Polyno-
mial.coeff q i
   by (metis (no-types, lifting) Multiv-Poly-Props.one-less-degree-def Polynomial.coeff-diff
Polynomial.coeff-monom assms coeffs-eq-Nil diff-zero length-0-conv length-coeffs-degree
less-Suc-eq-0-disj not-less-eq one-less-degree-degree)
  then have ∀ i < length ?sub-list. ?sub-list ! i = (Polynomial.coeffs q) ! i
    unfolding Polynomial.coeffs-def
    by (smt (verit, ccfv-SIG) add-0 assms degree-0 diff-zero length-map length-upt
less-Suc-eq less-nat-zero-code list.size(3) nth-map-upt one-less-degree-degree order.strict-trans)

  then show ?thesis
    using sublist-prefix-property assms
     by (smt (verit, del-insts) Suc-mono bot-nat-0.not-eq-extremum coeffs-eq-Nil
degree-0 length-coeffs-degree less-imp-le-nat list.size(3) one-less-degree-degree or-
der-less-subst1)
qed

lemma one-less-degree-is-strict-prefix:
  assumes Polynomial.degree q > 0
  shows Sublist.strict-prefix (Polynomial.coeffs (Multiv-Poly-Props.one-less-degree
q)) (Polynomial.coeffs q)
proof −
  have length (Polynomial.coeffs (Multiv-Poly-Props.one-less-degree q)) < length
```

```
(Polynomial.coeffs q)
    using one-less-degree-degree[of q]
      assms
   by (metis coeffs-0-eq-Nil degree-0 length-coeffs-degree less-nat-zero-code list.size(3)
not-less-eq)
  then show ?thesis
    using one-less-degree-is-prefix assms
    by (metis less-irrefl-nat prefix-order.order-iff-strict)
qed

lemma coeff-one-less-degree-var:
  assumes 0 < Polynomial.degree p
  assumes one-less-degree p ≠ 0
  shows i ≤ Polynomial.degree (one-less-degree p) ⟹
      poly.coeff p i = poly.coeff (one-less-degree p) i
proof −
  fix i
  assume i-leq: i ≤ Polynomial.degree (one-less-degree p)
  then have i-lt: i < length (Polynomial.coeffs (Multiv-Poly-Props.one-less-degree
p))
    unfolding Polynomial.coeffs-def using assms by auto
  have i-lt2: i < (Polynomial.degree p)
    using i-leq one-less-degree-degree[of p] assms(1) by auto
   have len-map1: length (map (poly.coeff p) [0..<Suc (Polynomial.degree p)]) =
Polynomial.degree p + 1
    by auto
  have len-map2: length (Polynomial.coeffs (Multiv-Poly-Props.one-less-degree p))
    = Polynomial.degree (one-less-degree p) + 1
    unfolding Polynomial.coeffs-def using assms(2) by auto
  have p ≠ 0
    using assms(1) by auto
  then have same-coeff: poly.coeff p i = (Polynomial.coeffs) p ! i
    unfolding  Polynomial.coeffs-def using assms i-lt2 len-map1
   by (smt (verit, best) Suc-eq-plus1 add-0 le-simps(2) length-map less-imp-le-nat
nth-map nth-upt)
  obtain zs where zs-prop: Polynomial.coeffs p =
        (Polynomial.coeffs (Multiv-Poly-Props.one-less-degree p)) @ zs
    using assms i-leq one-less-degree-is-prefix[of p] unfolding prefix-def
    by auto
  have same-coeff-2: ((Polynomial.coeffs (Multiv-Poly-Props.one-less-degree p)) @
zs) ! i =
    (Polynomial.coeffs (one-less-degree p)) ! i
    using i-lt
    by (simp add: nth-append)
  show poly.coeff p i = poly.coeff (one-less-degree p) i
    using same-coeff same-coeff-2 zs-prop
    by (simp add: i-lt nth-coeffs-coeff)
qed
```

lemma *coeff-one-less-degree*:
assumes *one-less-degree p* $\neq$ *0*
shows *i* $\leq$ *Polynomial.degree* (*one-less-degree p*) $\Longrightarrow$
poly.coeff p i = *poly.coeff* (*one-less-degree p*) *i*
proof −
have *Polynomial.degree p* > *0*
using *assms*
by (*metis* (*no-types*, *lifting*) *Multiv-Poly-Props.one-less-degree-def Polynomial.coeff-diff Polynomial.coeff-monom diff-zero eq-iff-diff-eq-0 eq-iff-diff-eq-0 le-degree leading-coeff-0-iff linorder-not-less zero-less-iff-neq-zero*)
then show $\bigwedge$*i*. *i* $\leq$ *Polynomial.degree* (*one-less-degree p*) $\Longrightarrow$
poly.coeff p i = *poly.coeff* (*one-less-degree p*) *i*
using *coeff-one-less-degree-var assms*
by *auto*
qed

lemma *coeff-one-less-degree-subset*:
assumes *one-less-degree q* $\neq$ *0*
shows *set* (*Polynomial.coeffs* (*Multiv-Poly-Props.one-less-degree q*)) $\subseteq$ *set* (*Polynomial.coeffs q*)
proof *clarsimp*
fix *x*
assume *x* $\in$ *set* (*Polynomial.coeffs* (*Multiv-Poly-Props.one-less-degree q*))
then obtain *i* **where** *i-prop*: *i* $\leq$ *Polynomial.degree* (*one-less-degree q*)
x = *poly.coeff* (*one-less-degree q*) *i*
unfolding *Polynomial.coeffs-def* **using** *assms*
using *atMost-upto* **by** *auto*
have *Polynomial.degree q* > *0*
using *assms*
by (*metis* (*no-types*, *lifting*) *Multiv-Poly-Props.one-less-degree-def Polynomial.coeff-diff Polynomial.coeff-monom diff-zero eq-iff-diff-eq-0 eq-iff-diff-eq-0 le-degree leading-coeff-0-iff linorder-not-less zero-less-iff-neq-zero*)
then show *x* $\in$ *set* (*Polynomial.coeffs q*)
using *coeff-one-less-degree assms i-prop*
unfolding *Polynomial.coeffs-def* **using** *one-less-degree-degree*
by (*smt* (*verit*, *best*) *Polynomial.coeffs-def coeff-in-coeffs degree-0 le-trans less-imp-le-nat less-numeral-extra*(*3*))
qed

lemma *coeffs-between-one-less-degree*:
assumes *0* < *Polynomial.degree p*
assumes *igt*: *i* > *Polynomial.degree* (*one-less-degree p*)
assumes *ilt*: *i* < *Polynomial.degree p*
shows *poly.coeff p i* = *0*
using *assms*
using *Multiv-Poly-Props.one-less-degree-def coeff-eq-0* **by** *fastforce*

lemma *poly-p-altdef-one-less-degree*:

assumes *deg-gt*: *Polynomial.degree p > 0*
assumes *deg-is*: *Polynomial.degree p = d*
shows *poly p x* = (∑ *i*≤*Polynomial.degree* (*one-less-degree p*). *Polynomial.coeff* (*one-less-degree p*) *i* * *x* ^ *i*)
+ (*Polynomial.coeff p d*)*(*x*^*d*)
proof −
let *?lp* = (*one-less-degree p*)
let *?deg-lp* = *Polynomial.degree ?lp*
have *poly p x* = (∑ *i*≤*d*. *Polynomial.coeff p i* * *x* ^ *i*)
using *assms poly-altdef* **by** *auto*
then have *p-is*: *poly p x* = (∑ *i*≤(*d* − *1*). *Polynomial.coeff p i* * *x* ^ *i*) + (*Polynomial.coeff p d*)*(*x*^*d*)
using *deg-gt*
by (*metis* (*no-types*, *lifting*) *One-nat-def Suc-pred assms*(*2*) *sum.atMost-Suc*)
have *well-def*: *?deg-lp* ≤ *d* − *1*
using *one-less-degree-degree deg-gt deg-is*
by (*metis One-nat-def Suc-pred less-Suc-eq-le*)
then have *sum1*: (∑ *i*≤(*d* − *1*). *Polynomial.coeff p i* * *x* ^ *i*) = (∑ *i*≤*Polynomial.degree ?lp*. *Polynomial.coeff p i* * *x* ^ *i*)
proof −
have ⋀*i*. (*i* > *Polynomial.degree ?lp* ∧ *i* ≤ *d* − *1*) ⟹ *Polynomial.coeff p i* = *0*
using *deg-is coeffs-between-one-less-degree*
by (*metis One-nat-def Suc-pred deg-gt less-Suc-eq-le*)
then show *?thesis* **using** *well-def*
proof (*induct d* − *1* − *?deg-lp arbitrary*: *d*)
case *0*
then show *?case*
by (*metis* (*no-types*, *lifting*) *diff-is-0-eq le-antisym*)
next
case (*Suc xa*)
then have *sum*: (∑ *i*≤*d* − *1*. *poly.coeff p i* * *x* ^ *i*) =
(∑ *i*≤*d* − *2*. *poly.coeff p i* * *x* ^ *i*) + (*poly.coeff p* (*d*−*1*) * *x* ^ (*d*−*1*))
using *Nat.diff-diff-right One-nat-def Suc-le-mono Suc-pred add-diff-cancel-right' bot-nat-0.not-eq-extremum diff-is-0-eq le-numeral-extra*(*4*) *nat-1-add-1 sum.atMost-Suc zero-le*
by (*smt* (*verit*, *del-insts*))
have *h0*: *xa* = *d* − *1* − *1* − *Polynomial.degree* (*Multiv-Poly-Props.one-less-degree p*)
using *Suc.hyps*(*2*) **by** *auto*
have *h1*: (⋀*i*. *Polynomial.degree* (*Multiv-Poly-Props.one-less-degree p*) < *i* ∧
i ≤ *d* − *1* − *1* ⟹
poly.coeff p i = *0*)
using *Suc.prems*(*1*) **by** *auto*
have *h2*: *Polynomial.degree* (*Multiv-Poly-Props.one-less-degree p*) ≤ *d* − *1* − *1*
using *Suc.prems Suc.hyps*(*2*) **by** *auto*
have *eq1*: (∑ *i*≤*d* − *2*. *poly.coeff p i* * *x* ^ *i*) = (∑ *i*≤*Polynomial.degree ?lp*. *Polynomial.coeff p i* * *x* ^ *i*)

using *Suc.hyps*(*1*)[*OF h0 h1 h2*]
by (*metis* (*no-types*, *lifting*) *diff-diff-left one-add-one*)
have *dgt*: *d* − *1* > *Polynomial.degree* (*one-less-degree p*)
using *Suc.prems Suc.hyps*(*2*) **by** *auto*
have *eq2*: *poly.coeff p* (*d*−*1*) = *0*
using *Suc.prems*
using *dgt* **by** *blast*
then show *?case* **using** *sum eq1 eq2*
by *fastforce*
qed
qed
have *sum2*: (∑ *i*≤*Polynomial.degree* (*one-less-degree p*). *Polynomial.coeff p i* ∗ *x* ^ *i*)
= (∑ *i*≤*Polynomial.degree* (*one-less-degree p*). *Polynomial.coeff* (*one-less-degree p*) *i* ∗ *x* ^ *i*)
using *coeff-one-less-degree*
by (*smt* (*verit*, *del-insts*) *Multiv-Poly-Props.one-less-degree-def Polynomial.coeff-monom atMost-iff bot-nat-0.extremum-uniqueI deg-gt degree-0 eq-iff-diff-eq-0 leading-coeff-0-iff nat-neq-iff sum.cong*)
then show *?thesis*
using *p-is sum1 sum2*
by *presburger*
qed

4 Expressing as univariate

definition *transform*:: *real mpoly list* ⇒ *real mpoly Polynomial.poly list*
where *transform qs* = (*let vs* = *variables-list qs in*
map (λ*q*. (*mpoly-to-mpoly-poly* (*nth vs* (*length vs* − *1*)) *q*)) *qs*)

definition *mpoly-to-mpoly-poly-alt* :: *nat* ⇒ *'a* :: *comm-ring-1 mpoly* ⇒ *'a mpoly Polynomial.poly* **where**
mpoly-to-mpoly-poly-alt x p = (∑ *i*∈{*0*..*MPoly-Type.degree p x*} .
Polynomial.monom (*isolate-variable-sparse p x i*) *i*)

definition *univariate-in*:: *real mpoly list* ⇒ *nat* ⇒ *real mpoly Polynomial.poly list*
where *univariate-in qs i* = *map* (*mpoly-to-mpoly-poly-alt i*) *qs*

lemma *degree-less-sum-max*:
shows *MPoly-Type.degree* (*p*+*q*) *var* ≤ *max* (*MPoly-Type.degree p var*) (*MPoly-Type.degree q var*)
by (*simp add*: *degree-add-leq*)

lemma *mpoly-to-mpoly-poly-alt-sum-aux* :
shows (∑ *i* = *0*..*b*.
Polynomial.monom (*isolate-variable-sparse* (*p* + *q*) *x i*) *i*) =
(∑ *i* = *0*..*b*. *Polynomial.monom* (*isolate-variable-sparse p x i*) *i*) +
(∑ *i* = *0*..*b*. *Polynomial.monom* (*isolate-variable-sparse q x i*) *i*)
proof (*induct b*)

```
  case 0
  then show ?case using isovarspar-sum[of p q x 0]
    by (simp add: add-monom)
next
  case (Suc x)
  then show ?case
    using isovarspar-sum[of p q x Suc x]
  proof −
     have f1: (∑ n = 0..x. Polynomial.monom (isolate-variable-sparse (p + q)
x n) n) = (∑ n = 0..x. Polynomial.monom (isolate-variable-sparse p x n) n +
Polynomial.monom (isolate-variable-sparse q x n) n)
      by (simp add: isovarspar-sum monom-hom.hom-add)
      have Polynomial.monom (isolate-variable-sparse (p + q) x (Suc x)) (Suc
x) = Polynomial.monom (isolate-variable-sparse p x (Suc x)) (Suc x) + Poly-
nomial.monom (isolate-variable-sparse q x (Suc x)) (Suc x)
      by (simp add: add-monom isovarspar-sum)
   then have (∑ n = 0..x. Polynomial.monom (isolate-variable-sparse (p + q) x n)
n) + Polynomial.monom (isolate-variable-sparse (p + q) x (Suc x)) (Suc x) = (∑ n
= 0..x. Polynomial.monom (isolate-variable-sparse p x n) n + Polynomial.monom
(isolate-variable-sparse q x n) n) + (Polynomial.monom (isolate-variable-sparse p
x (Suc x)) (Suc x) + Polynomial.monom (isolate-variable-sparse q x (Suc x)) (Suc
x))
      using f1 by presburger
     then have (∑ n = 0..Suc x. Polynomial.monom (isolate-variable-sparse (p
+ q) x n) n) = (∑ n = 0..x. Polynomial.monom (isolate-variable-sparse p x n)
n + Polynomial.monom (isolate-variable-sparse q x n) n) + (Polynomial.monom
(isolate-variable-sparse p x (Suc x)) (Suc x) + Polynomial.monom (isolate-variable-sparse
q x (Suc x)) (Suc x))
      by (smt (z3) sum.atLeast0-atMost-Suc)
    then have (∑ n = 0..Suc x. Polynomial.monom (isolate-variable-sparse (p +
q) x n) n) = (∑ n = 0..Suc x. Polynomial.monom (isolate-variable-sparse p x n)
n + Polynomial.monom (isolate-variable-sparse q x n) n)
      by (smt (z3) sum.atLeast0-atMost-Suc)
    then show ?thesis
    by (smt (z3) Suc add-monom isovarspar-sum sum.atLeast0-atMost-Suc sum.distrib)
  qed
qed

lemma isovar-sum-to-higher-degree:
  assumes b ≥ (MPoly-Type.degree p x)
  shows (∑ i = 0..(MPoly-Type.degree p x). Polynomial.monom (isolate-variable-sparse
p x i) i) =
 (∑ i = 0..b. Polynomial.monom (isolate-variable-sparse p x i) i)
  using assms
proof (induct b)
  case 0
  then show ?case
    by auto
next
```

```
  case (Suc b)
  then show ?case using isovar-greater-degree
   by (smt (z3) Orderings.order-eq-iff add.commute add-0 isolate-variable-sparse-ne-zeroD
le-SucE monom-hom.hom-zero sum.atLeast0-atMost-Suc)
qed

lemma mpoly-to-mpoly-poly-alt-sum :
 shows mpoly-to-mpoly-poly-alt x (p+q) = (mpoly-to-mpoly-poly-alt x p) + (mpoly-to-mpoly-poly-alt
x q)
proof −
  let ?deg = max (MPoly-Type.degree p x) (MPoly-Type.degree q x)
  have (∑ i = 0..MPoly-Type.degree (p + q) x.
        Polynomial.monom (isolate-variable-sparse (p + q) x i) i) =
    (∑ i = 0..MPoly-Type.degree p x. Polynomial.monom (isolate-variable-sparse
p x i) i) +
    (∑ i = 0..MPoly-Type.degree q x. Polynomial.monom (isolate-variable-sparse q
x i) i)
  proof (induct ?deg arbitrary: p q)
    case 0
    then have MPoly-Type.degree (p + q) x = 0 ∧ MPoly-Type.degree p x = 0 ∧
MPoly-Type.degree q x = 0
      using degree-add-leq[of p x 0 q]
      by (metis le-zero-eq max.cobounded1 max.cobounded2)
    then show ?case
      using isovarspar-sum[of p q x]
      by (simp add: add-monom)
  next
    case (Suc xa)
    let ?deg-sum = MPoly-Type.degree (p+q) x
    let ?deg-p = (MPoly-Type.degree p x)
    let ?deg-q = (MPoly-Type.degree q x)
    have ?deg-sum = max ?deg-p ?deg-q ∨ ?deg-sum < max ?deg-p ?deg-q
      using degree-less-sum-max[of p q x] by auto
    moreover {
      assume ∗: ?deg-sum = max ?deg-p ?deg-q
       have eq1: (∑ i = 0..?deg-p. Polynomial.monom (isolate-variable-sparse p x
i) i) =
 (∑ i = 0..?deg-sum. Polynomial.monom (isolate-variable-sparse p x i) i)
 using ∗ isovar-sum-to-higher-degree
        by (simp add: isovar-sum-to-higher-degree)
       have eq2: (∑ i = 0..?deg-q. Polynomial.monom (isolate-variable-sparse q x
i) i) =
 (∑ i = 0..?deg-sum. Polynomial.monom (isolate-variable-sparse q x i) i)
        using ∗ isovar-sum-to-higher-degree
        by (simp add: isovar-sum-to-higher-degree)
      then have (∑ i = 0..?deg-sum.
            Polynomial.monom (isolate-variable-sparse (p + q) x i) i) =
          (∑ i = 0..?deg-p. Polynomial.monom (isolate-variable-sparse p x i) i) +
          (∑ i = 0..?deg-q. Polynomial.monom (isolate-variable-sparse q x i) i)
```

```
      by (simp add: eq1 eq2 mpoly-to-mpoly-poly-alt-sum-aux)
  }
  moreover {
    assume *: ?deg-sum < max ?deg-p ?deg-q
    let ?mx = max ?deg-p ?deg-q
     have eq1: (∑ i = 0..?deg-p. Polynomial.monom (isolate-variable-sparse p x
i) i) =
 (∑ i = 0..?mx. Polynomial.monom (isolate-variable-sparse p x i) i)
 using * isovar-sum-to-higher-degree
      by (simp add: isovar-sum-to-higher-degree)
     have eq2: (∑ i = 0..?deg-q. Polynomial.monom (isolate-variable-sparse q x
i) i) =
 (∑ i = 0..?mx. Polynomial.monom (isolate-variable-sparse q x i) i)
      using * isovar-sum-to-higher-degree
      by (simp add: isovar-sum-to-higher-degree)
    have eq3: (∑ i = 0..?deg-sum. Polynomial.monom (isolate-variable-sparse (p
+ q) x i) i) =
     (∑ i = 0..?mx. Polynomial.monom (isolate-variable-sparse (p + q) x i) i)
      using * isovar-sum-to-higher-degree
      by (simp add: isovar-sum-to-higher-degree)
     then have (∑ i = 0..?deg-sum.
           Polynomial.monom (isolate-variable-sparse (p + q) x i) i) =
       (∑ i = 0..?deg-p. Polynomial.monom (isolate-variable-sparse p x i) i) +
       (∑ i = 0..?deg-q. Polynomial.monom (isolate-variable-sparse q x i) i)
      using mpoly-to-mpoly-poly-alt-sum-aux eq1 eq2 eq3
      by auto
  }
  ultimately have  (∑ i = 0..?deg-sum.
           Polynomial.monom (isolate-variable-sparse (p + q) x i) i) =
       (∑ i = 0..?deg-p. Polynomial.monom (isolate-variable-sparse p x i) i) +
       (∑ i = 0..?deg-q. Polynomial.monom (isolate-variable-sparse q x i) i)
    by fastforce
  then show ?case
    by fastforce
 qed
 then show ?thesis
  by (simp add: mpoly-to-mpoly-poly-alt-def)
qed

lemma multivar-as-univar: mpoly-to-mpoly-poly-alt x p = mpoly-to-mpoly-poly x p
proof (induct p rule: mpoly-induct)
 case (monom m a)
 have a = 0 ∨ a ≠ 0 by auto
 moreover {
  assume *: a = 0
  then have  mpoly-to-mpoly-poly-alt x (MPoly-Type.monom m a) =
        mpoly-to-mpoly-poly x (MPoly-Type.monom m a)
    using mpoly-to-mpoly-poly-monom[of x m a]
    unfolding mpoly-to-mpoly-poly-alt-def
```

```
      isolate-variable-sparse-monom[of m a]
    by auto
 }
 moreover {
  assume *: a ≠0
  then  have monomials (MPoly-Type.monom m a) = {m}
    using MPolyExtension.monomials-monom by auto
  then have (lookup m x) = MPoly-Type.degree (MPoly-Type.monom m a) x
    using degree-eq-iff[of (MPoly-Type.monom m a) x]
    by (simp add: * degree-monom)
  then have h1: (∑ i = 0..MPoly-Type.degree (MPoly-Type.monom m a) x.
      Polynomial.monom (isolate-variable-sparse (MPoly-Type.monom m a) x i)
i) =
      (∑ i = 0..(lookup m x).
      Polynomial.monom (isolate-variable-sparse (MPoly-Type.monom m a) x i)
i)
    by auto
  have ⋀i. i < (lookup m x ) ⟹
  Polynomial.monom (isolate-variable-sparse (MPoly-Type.monom m a) x i) i =
0
    using isolate-variable-sparse-monom[of m a]
    by auto
  then have (∑ i = 0..<(lookup m x).
      Polynomial.monom (isolate-variable-sparse (MPoly-Type.monom m a) x i)
i) = 0
    by simp
  then have h2: (∑ i = 0..(lookup m x).
     Polynomial.monom (isolate-variable-sparse (MPoly-Type.monom m a) x i) i)
= Polynomial.monom (isolate-variable-sparse (MPoly-Type.monom m a) x (lookup
m x))
        (lookup m x)
    by (simp add: sum.head-if)
  have k1: (∑ i = 0..MPoly-Type.degree (MPoly-Type.monom m a) x.
      Polynomial.monom (isolate-variable-sparse (MPoly-Type.monom m a) x i)
i) =
       Polynomial.monom (isolate-variable-sparse (MPoly-Type.monom m a) x
(lookup m x))
        (lookup m x)
    using h1 h2 by auto
  have Abs-poly-mapping ((lookup m)(x := 0)) =
  Abs-poly-mapping (λk. lookup m k when k ≠ x)
    by (metis (full-types) when(1) when(2) fun-upd-apply)
  then have (Poly-Mapping.update x 0 m) = (remove-key x m)
    unfolding remove-key-def update-def
    by (auto)
 then have MPoly-Type.monom (Poly-Mapping.update x 0 m) a = MPoly-Type.monom
(remove-key x m) a
    by auto
  then have isolate-variable-sparse (MPoly-Type.monom m a) x (lookup m x) =
```

MPoly-Type.monom (*remove-key x m*) *a*
using *ExecutiblePolyProps.isolate-variable-sparse-monom*[*of m a x* (*lookup m x*)] ∗
by *auto*
then have *k2*: *Polynomial.monom* (*isolate-variable-sparse* (*MPoly-Type.monom m a*) *x* (*lookup m x*)) (*lookup m x*) = *Polynomial.monom* (*MPoly-Type.monom* (*remove-key x m*) *a*) (*lookup m x*)
by *auto*
have *mpoly-to-mpoly-poly-alt x* (*MPoly-Type.monom m a*) = *mpoly-to-mpoly-poly x* (*MPoly-Type.monom m a*) **unfolding** *mpoly-to-mpoly-poly-alt-def*
using *k1 k2 mpoly-to-mpoly-poly-monom*[*of x m a*]
by *auto*
}
ultimately have *mpoly-to-mpoly-poly-alt x* (*MPoly-Type.monom m a*) = *mpoly-to-mpoly-poly x* (*MPoly-Type.monom m a*)
by *blast*
then show *?case*
by *blast*
next
case (*sum p1 p2 m a*)
then show *?case*
using *mpoly-to-mpoly-poly-add*[*of x p1 p2*] *mpoly-to-mpoly-poly-alt-sum*[*of x p1 p2*]
by *auto*
qed

5 Same mpoly eval means same polynomials

lemma *var-in-some-coeff*:
fixes *p*::*real mpoly Polynomial.poly*
fixes *w*::*real mpoly*
assumes *x* ∈ *vars* ((*poly p w*)::*real mpoly*)
shows *x* ∈ *vars w* ∨ (∃ *i*. *x* ∈ *vars* (*poly.coeff p i*))
using *assms*
proof (*induct Polynomial.degree p arbitrary*: *p rule*: *less-induct*)
case *less*
{assume ∗: *Polynomial.degree p* = *0*
then have *x* ∈ *vars w* ∨ (∃ *i*. *x* ∈ *vars* (*poly.coeff p i*))
using *poly-altdef*[*of p w*]
using *local.less*(*2*) **by** *force*
} moreover
{assume ∗: *Polynomial.degree p* > *0*
then obtain *xa* **where** *deg-is*: *Polynomial.degree p* = *xa* + *1*
by (*metis Suc-eq-plus1 less-numeral-extra*(*3*) *not0-implies-Suc*)
then have *poly-p-w*: *poly p w* = (∑ *i*≤*xa*. *poly.coeff p i* ∗ *w* ^ *i*) + (*poly.coeff p* (*xa* + *1*) ∗ *w* ^ (*xa* + *1*))
using *poly-altdef*[*of p w*]
by (*metis* (*no-types*, *lifting*) *Suc-eq-plus1 sum.atMost-Suc*)

```
    then have xin: x ∈ vars (∑ i≤xa. poly.coeff p i * w ^ i) ∨ x ∈ vars (poly.coeff
p (xa + 1) * w ^ (xa + 1))
      using vars-add
      using local.less(2) by auto
    let ?q = one-less-degree p
    have less-deg: (poly (one-less-degree p) w) = (∑ i≤xa. poly.coeff p i * w ^ i)
      using coeff-one-less-degree poly-altdef deg-is
      by (smt (verit, best) local.less(2) Suc-eq-plus1 poly-p-w add-diff-cancel-right'
poly-p-altdef-one-less-degree sum.cong zero-less-Suc)
    {assume **: x ∈ vars (poly.coeff p (xa + 1) * w ^ (xa + 1))
      then have x ∈ vars w ∨ (∃ i. x ∈ vars (poly.coeff p i))
        using vars-mult[of poly.coeff p (xa + 1) w ^ (xa + 1)]
        by (meson not-in-mult not-in-pow)
    }
    moreover {assume **:x ∈ vars (∑ i≤xa. poly.coeff p i * w ^ i)
      then have x ∈ vars (poly (one-less-degree p) w)
        using less-deg by auto
      then have x ∈ vars w ∨ (∃ i. x ∈ vars (poly.coeff (one-less-degree p) i))
        using less.hyps one-less-degree-degree *
        by simp
      then have x ∈ vars w ∨ (∃ i. x ∈ vars (poly.coeff p i))
        using coeff-one-less-degree
        by (metis coeff-eq-0 le-degree lessI zero-poly.rep-eq)
    }
    ultimately have  x ∈ vars w ∨ (∃ i. x ∈ vars (poly.coeff p i))
      using xin
      by auto
  } ultimately show ?case
    by auto
qed

fun zero-list:: nat ⇒ ('a::zero) list
  where zero-list 0 = []
  | zero-list (Suc n) = (0::'a)#(zero-list n)

lemma zero-list-len:
  shows length (zero-list n) = n
proof (induct n)
  case 0
  then show ?case by auto
next
  case (Suc n)
  then show ?case by auto
qed




lemma zero-list-member:
```

```
  shows m < n ⟹ (zero-list n) ! m = 0
proof −
  assume m < n
  then show (zero-list n) ! m = 0
    proof (induct n arbitrary: m)
      case 0
      then show ?case by auto
    next
      case (Suc n)
      then show ?case
        using less-Suc-eq-0-disj by force
    qed
qed

lemma eval-mpoly-zero-is-zero:
  assumes all-same: ⋀ L. eval-mpoly L p = 0
  shows p = 0
  using assms
proof (induct List.length (sorted-list-of-set (vars p)) arbitrary: p rule: less-induct)
  case less
  {assume ∗: vars p = {}
    then obtain k where k-prop: p = Const k
      using vars-empty-iff
      by blast
    then have k ≠ 0 ⟹ False using all-same
    proof −
      assume ∗:k≠ 0
      have eval-mpoly [1] p = k
        using k-prop unfolding eval-mpoly-def
        by auto
      then show False
        using less.prems ∗ by auto
    qed
    then have  p = 0
      using k-prop
      using mpoly-Const-0
      by blast
  }
  moreover {assume ∗: vars p ≠ {}
    then obtain k where k ∈ vars p
      by blast
    then have MPoly-Type.degree p k > 0
      using degree-pos-iff by blast
    let ?uni-conn = mpoly-to-mpoly-poly-alt k p
    have Polynomial.degree ?uni-conn > 0
      by (simp add: ‹0 < MPoly-Type.degree p k› multivar-as-univar)
    then have ?uni-conn ≠ 0
      by auto
    then have finset: finite {x. Polynomial.poly ?uni-conn x = 0}
```

```
    using poly-roots-finite[of ?uni-conn]
    by blast
  then have ∃(w::real). Polynomial.poly ?uni-conn (Const w) ≠ 0
  proof −
   have (∀(w::real). Const w ∈ {x. Polynomial.poly ?uni-conn x = 0}) ⟹ False
    proof −
     assume ∀ w. Const w ∈ {x. Polynomial.poly ?uni-conn x = 0}
      then have subset: {x. ∃ (w::real). Const w = x} ⊆{x. Polynomial.poly
?uni-conn x = 0}
       by auto
      have bij-betw (λx::real. Const x) {x. ∃(w::real). w = x} {x. ∃ (w::real).
Const w = x}
      proof −
       have h1: inj-on Const {x. ∃ w. w = x}
        unfolding inj-on-def by auto
       have h2: Const ' {x. ∃ w. w = x} = {x. ∃ w. Const w = x}
        unfolding image-def by auto
       show ?thesis using h1 h2 unfolding bij-betw-def
        by auto
      qed
      then have set-eq: finite {x. ∃(w::real). w = x} = finite {x. ∃ (w::real).
Const w = x}
       using bij-betw-finite[of - {x. ∃(w::real). w = x} {x. ∃ w. Const w = x}]
       by auto
      have h1: ¬ (finite {x. ∃(w::real). w = x} )
       using infinite-UNIV-char-0
       by auto
      then have ¬ (finite {x. ∃ (w::real). Const w = x})
       using set-eq h1 by auto
      then have ¬ (finite {x. Polynomial.poly ?uni-conn x = 0})
       using subset infinite-super by auto
      then show False using finset
       by auto
    qed
    then show ?thesis
     by auto
  qed
   then obtain w where w-prop: ((Polynomial.poly ?uni-conn (Const w))::real
mpoly) ≠ 0
    by auto
  have vars: vars ((Polynomial.poly ?uni-conn (Const w))::real mpoly) ⊆ vars p
− {k}
  proof
   fix x
   assume ∗: x ∈ vars (poly (mpoly-to-mpoly-poly-alt k p) (Const w))
   have vars (Const w) = {} by auto
   then have ex-i: ∃ i. x ∈ vars (poly.coeff (mpoly-to-mpoly-poly k p) i)
    using var-in-some-coeff ∗
    by (metis empty-iff multivar-as-univar)
```

show $x \in vars\ p - \{k\}$
using *multivar-as-univar vars-coeff-mpoly-to-mpoly-poly*
using *ex-i* **by** *blast*
qed
then have *card* (*vars* (*poly* (*mpoly-to-mpoly-poly-alt k p*) (*Const w*))) < *card* (*vars p*)
by (*metis Diff-subset* ‹*k* ∈ *vars p*› *card-Diff1-less order-neq-le-trans psubset-card-mono psubset-subset-trans vars-finite*)
then have *vars-len*: *length* (*sorted-list-of-set* (*vars* (*Polynomial.poly ?uni-conn* (*Const w*)))) < *length* (*sorted-list-of-set* (*vars p*))
by *auto*
then have ∃ *z*. *eval-mpoly z* (*Polynomial.poly ?uni-conn* (*Const w*)) ≠ *0*
proof −
have (⋀*L*. *eval-mpoly L* (*Polynomial.poly ?uni-conn* (*Const w*)) = *0*) ⟹ (*Polynomial.poly ?uni-conn* (*Const w*)) = *0*
using *vars-len less.hyps* **by** *auto*
then show *?thesis* **using** *w-prop* **by** *auto*
qed
then obtain *z* **where** *z-prop*: *eval-mpoly z* (*Polynomial.poly ?uni-conn* (*Const w*)) ≠ *0*
by *auto*
obtain *update-z* **where** *update-z-prop*: *update-z* = (*if length z* > *k then z else append z* (*zero-list* (*k* − (*length z*) + *1*)))
by *simp*
then have *update-z-len*: *length update-z* ≥ *k*
using *zero-list-len*
by (*smt* (*z3*) *add-diff-inverse-nat length-append less-or-eq-imp-le linorder-le-less-linear nat-add-left-cancel-less not-add-less1*)
obtain *ell* **where** *ell-prop*:
ell = *list-update update-z k w*
(∀ *i* ≠ *k*. *ell* ! *i* = *update-z* ! *i*) ∧ *ell* ! *k* = *w*
using *update-z-len*
by (*simp add*: *update-z-prop zero-list-len*)
have *k-notin*: *k* ∉ *vars* (*Polynomial.poly ?uni-conn* (*Const w*))
by (*meson DiffE singletonI subsetD vars*)
then have *eval-mpoly update-z* (*Polynomial.poly ?uni-conn* (*Const w*)) = *eval-mpoly ell* (*Polynomial.poly ?uni-conn* (*Const w*))
unfolding *eval-mpoly-def*
by (*metis ell-prop*(*1*) *list-update-id not-contains-insertion*)
have *same-except1*: (⋀*y*. *y* ≠ *k* ⟹ *nth-default 0 update-z y* = *nth-default 0 ell y*)
using *update-z-prop*
by (*metis ell-prop*(*1*) *ell-prop*(*2*) *length-list-update nth-default-eq-dflt-iff nth-default-nth*)

have *same-except2*: (⋀*y*. *y* ≠ *k* ⟹ *nth-default 0 update-z y* = *nth-default 0 z y*)
proof −
fix *y*

assume *y-not*: $y \neq k$
{assume $*$: $y \geq (length\ z)$
then have *h1*: *nth-default 0 z y = 0*
unfolding *nth-default-def*
by *auto*
have *h2*: *nth-default 0 update-z y = 0*
unfolding *nth-default-def* **using** *y-not update-z-prop zero-list-member*
by (*smt* (*z3*) $*$ *add-diff-cancel-left' diff-less-mono length-append linorder-not-le nth-append zero-list-len*)
then have *nth-default 0 update-z y = nth-default 0 z y*
using *h1 h2*
by *auto*
} moreover
{assume $*$: $y < (length\ z)$
then have *nth-default 0 update-z y = nth-default 0 z y*
using *update-z-prop y-not*
by (*metis nth-default-append nth-default-nth*)
}
ultimately show *nth-default 0 update-z y = nth-default 0 z y* **using** *update-z-prop zero-list-member*
using *linorder-le-less-linear* **by** *blast*
qed
have *h*: $(\bigwedge y.\ y \neq k \Longrightarrow$ *nth-default 0 z y = nth-default 0 ell y*)
using *same-except1 same-except2*
by *auto*
then have *same1*: *poly* (*map-poly* (*insertion* (*nth-default 0 z*)) (*mpoly-to-mpoly-poly k p*)) *w* =
(*insertion* (*nth-default 0 ell*)) *p*
using *insertion-mpoly-to-mpoly-poly*[*of k* (*nth-default 0 z*) (*nth-default 0 ell*) *p*]
ell-prop(*2*)
by (*smt* (*verit*, *del-insts*) *One-nat-def add-Suc-right add-diff-inverse-nat ell-prop*(*1*) *length-append length-list-update lessI nth-default-def semiring-norm*(*51*) *update-z-prop zero-list-len*)
have *same2*: *poly* (*map-poly* (*insertion* (*nth-default 0 z*)) (*mpoly-to-mpoly-poly k p*)) *w*
= *eval-mpoly z* (*Polynomial.poly ?uni-conn* (*Const w*))
unfolding *eval-mpoly-def poly-def*
by (*smt* (*verit*, *best*) *One-nat-def h* ‹*eval-mpoly z* (*poly* (*mpoly-to-mpoly-poly-alt k p*) (*Const w*)) $\neq$ *0*› *k-notin add-diff-inverse-nat arith-extra-simps*(*6*) *ell-prop*(*1*) *eval-mpoly-def eval-mpoly-map-poly-comm-ring-hom.base.poly-map-poly insertion-const insertion-irrelevant-vars insertion-var length-append less.prems lessI multivar-as-univar nat-add-left-cancel-less poly-mpoly-to-mpoly-poly update-z-prop zero-list-len*)
have *same3*: *eval-mpoly ell p = eval-mpoly z* (*Polynomial.poly ?uni-conn* (*Const w*))
using *same1 same2*
using *eval-mpoly-def* **by** *force*
then have *eval-mpoly ell p* $\neq$ *0*
using *z-prop*

by *presburger*
then have *mpoly-to-mpoly-poly-alt k p ≠ 0 ⟹ False*
using *insertion-mpoly-to-mpoly-poly w-prop*
by (*meson local.less*(*2*))
then have *mpoly-to-mpoly-poly-alt k p = 0*
by *auto*
then have *p = 0*
using *multivar-as-univar*
by (*metis mpoly-to-mpoly-poly-0 mpoly-to-mpoly-poly-eq-iff*)
}
ultimately show *?case*
by *auto*
qed

6 Useful properties for decision proofs

lemma *eval-mpoly-same*:
assumes *all-same*: (⋀ *L*. *eval-mpoly L p = eval-mpoly L q*)
shows *p = q*
proof −
have ⋀ *L*. *eval-mpoly L* (*p* − *q*) = *0*
using *all-same*
using *eval-mpoly-map-poly-comm-ring-hom.base.hom-minus* **by** *fastforce*
then have *p* − *q* = *0*
using *eval-mpoly-zero-is-zero*
by *blast*
then show *?thesis*
by *auto*
qed

lemma *univariate-in-eval*:
fixes *qs*:: *real mpoly list*
fixes *x y*:: *real*
shows (*map* (λ*p*. (*Polynomial.poly p x*)) (*map* (λ*q*. *eval-mpoly-poly* (*y*#*xs*) *q*) (*univariate-in qs 0*))
= *map* (*eval-mpoly* (*x*#*xs*)) *qs*)
proof −
have ⋀*xa*. *xa* ∈ *set qs* ⟹
poly (*eval-mpoly-poly* (*y* # *xs*) (*mpoly-to-mpoly-poly-alt 0 xa*)) *x* =
eval-mpoly (*x* # *xs*) *xa*
proof −
fix *xa*
assume *xa* ∈ *set qs*
have (⋀*ya*. *ya* ≠ *0* ⟹ *nth-default 0* (*y* # *xs*) *ya* = *nth-default 0* (*x* # *xs*) *ya*)
by (*metis nat.exhaust nth-default-Cons-Suc*)
then show *poly* (*eval-mpoly-poly* (*y* # *xs*) (*mpoly-to-mpoly-poly-alt 0 xa*)) *x* =
eval-mpoly (*x* # *xs*) *xa*
unfolding *eval-mpoly-poly-def eval-mpoly-def*

```
    using insertion-mpoly-to-mpoly-poly[of 0 (nth-default 0 (y # xs))
       (nth-default 0 (x # xs)) xa]
      multivar-as-univar[of 0 xa]
    by auto
  qed
  then show ?thesis unfolding univariate-in-def
    by auto
qed



lemma lowering-poly-eval-var:
  fixes q:: real mpoly Polynomial.poly
  assumes not-in-vars: ∀ c ∈ set (Polynomial.coeffs q). 0 ∉ vars c
  assumes nonz: q ≠ 0
  fixes x y:: real
  shows eval-mpoly-poly xs (map-poly (lowerPoly 0 1) q)
    = eval-mpoly-poly (y#xs) q
proof −
  let ?map-lp-q = map-poly (lowerPoly 0 1) q
  have zero-prop: ⋀p. p ∈ set (Polynomial.coeffs q) ⟹ (lowerPoly 0 1 p = 0 ⟷
p = 0)
  proof −
    fix p
    assume ∗: p ∈ set (Polynomial.coeffs q)
    let ?lp = lowerPoly 0 1 p
    have ∀ r::real mpoly. r = 0 ⟷ (∀ val. eval-mpoly val r = 0)
      using eval-mpoly-zero-is-zero by auto
    have 0 ∉ vars p
      using ∗ not-in-vars by auto
    then have match: ∀ y. eval-mpoly (y # xs) p =  eval-mpoly xs ?lp
      by (simp add: eval-mpoly-def insertion-lowerPoly01)
    then have d1: lowerPoly 0 1 p = 0 ⟹ p = 0
    proof −
      assume is-zero: lowerPoly 0 1 p = 0
      then have ⋀ L. eval-mpoly L ?lp = 0
        using eval-mpoly-zero-is-zero by auto
      then have ⋀ L. eval-mpoly L p = 0
      proof −
        fix L:: real list
        { assume ∗: L = []
          then have same-eval: eval-mpoly (0 # L) p =  eval-mpoly L p
            unfolding eval-mpoly-def
             by (smt (verit, ccfv-threshold) add-0 insertion-irrelevant-vars less-Suc0
list.size(3) list.size(4) nth-Cons-0 nth-default-Nil nth-default-def)
          then have eval-mpoly (0 # L) p = eval-mpoly L ?lp
            using match
            by (simp add: ‹0 ∉ vars p› eval-mpoly-def insertion-lowerPoly01)
          then have eval-mpoly L p = 0
```

```
      using is-zero same-eval by auto
    } moreover { assume ∗: length L > 0
      then obtain h T where L = h # T
        by (metis length-greater-0-conv neq-Nil-conv)
      then have same-eval: eval-mpoly L p = eval-mpoly T ?lp
        using match
        by (simp add: ‹0 ∉ vars p› eval-mpoly-def insertion-lowerPoly01)
      then have eval-mpoly L p = 0
        using is-zero same-eval by auto
    }
    ultimately show eval-mpoly L p = 0
      by blast
  qed
  then show p = 0
    using eval-mpoly-zero-is-zero by auto
 qed
 have d2: p = 0 ⟹ lowerPoly 0 1 p = 0
  using match eval-mpoly-zero-is-zero
  using lower0 by blast
 then show (lowerPoly 0 1 p = 0 ⟷ p = 0)
  using d1 d2 by auto
qed
then have map-nonz: ?map-lp-q ≠ 0
 using nonz
 by (simp add: lower0 map-poly-eq-0-iff)
have Polynomial.degree q = length (Polynomial.coeffs q) − 1
 using nonz degree-eq-length-coeffs by auto
then have deg1: Polynomial.degree ?map-lp-q ≤ Polynomial.degree q
 unfolding map-poly-def
 by (metis degree-map-poly-le map-poly-def)
have deg2: Polynomial.degree ?map-lp-q ≥ Polynomial.degree q
 using zero-prop unfolding map-poly-def
 by (metis Ring-Hom-Poly.degree-map-poly coeff-in-coeffs le-degree leading-coeff-neq-0
map-poly-def nonz)
then have same-deg: Polynomial.degree q = Polynomial.degree ?map-lp-q
 using deg1 deg2 by auto
have q = poly-of-list (Polynomial.coeffs q)
 (map-poly (lowerPoly 0 1) q) = poly-of-list (Polynomial.coeffs (map-poly (lowerPoly
0 1) q))
 using Poly-coeffs by auto
have same-len: length (Polynomial.coeffs q) = length (Polynomial.coeffs (map-poly
(lowerPoly 0 1) q))
 using nonz same-deg degree-eq-length-coeffs map-nonz
 by (simp add: length-coeffs-degree)
have ⋀i. i < length (Polynomial.coeffs q) ⟹ eval-mpoly (y#xs) ((Polynomial.coeffs
q) ! i) = eval-mpoly xs ((Polynomial.coeffs (map-poly (lowerPoly 0 1) q)) ! i)
proof − fix i
 assume ∗: i < length (Polynomial.coeffs q)
 then have not-in-vars: 0 ∉ vars ((Polynomial.coeffs q) ! i)
```

using *not-in-vars*
by *auto*
then have *same-eval*: *eval-mpoly* (*y*#*xs*) ((*Polynomial.coeffs q*) ! *i*) = *eval-mpoly xs* ((*lowerPoly 0 1*) ((*Polynomial.coeffs q*) ! *i*))
by (*simp add*: *eval-mpoly-def insertion-lowerPoly01*)
have (*Polynomial.coeffs* (*map-poly* (*lowerPoly 0 1*) *q*)) ! *i* =
(*lowerPoly 0 1*) ((*Polynomial.coeffs q*) ! *i*)
using *coeff-map-poly lower0 same-len* ∗
by (*metis nth-coeffs-coeff*)
then show *eval-mpoly* (*y*#*xs*) ((*Polynomial.coeffs q*) ! *i*) = *eval-mpoly xs* ((*Polynomial.coeffs* (*map-poly* (*lowerPoly 0 1*) *q*)) ! *i*)
using *same-eval* **by** *auto*
qed
then show *?thesis* **unfolding** *eval-mpoly-poly-def map-poly-def*
using *same-len*
by (*metis map-poly-def nth-map-conv*)
qed

lemma *lowering-poly-eval*:
fixes *q*:: *real mpoly Polynomial.poly*
assumes ∀ *c* ∈ *set* (*Polynomial.coeffs q*). *0* ∉ *vars c*
fixes *x y*:: *real*
shows *eval-mpoly-poly xs* (*map-poly* (*lowerPoly 0 1*) *q*)
= *eval-mpoly-poly* (*y*#*xs*) *q*
using *lowering-poly-eval-var*
by (*metis assms eval-mpoly-poly-comm-ring-hom.hom-zero map-poly-0*)

lemma *reindexed-univ-qs-eval*:
assumes *univ-qs* = *univariate-in qs 0*
assumes *reindexed-univ-qs* = *map* (*map-poly* (*lowerPoly 0 1*)) *univ-qs*
shows *map* (*eval-mpoly* (*x*#*xs*)) *qs* =
(*map* (λ*p*. (*Polynomial.poly p x*)) (*map* (λ*q*. *eval-mpoly-poly xs q*) *reindexed-univ-qs*))
proof −
have *same*: ⋀*i*. *i* < *length reindexed-univ-qs* ⟹ (*map* (λ*p*. (*Polynomial.poly p x*)) (*map* (λ*q*. *eval-mpoly-poly xs q*) *reindexed-univ-qs*)) ! *i*
= (*Polynomial.poly* (*eval-mpoly-poly xs* (*reindexed-univ-qs* ! *i*)) *x*)
by *simp*
have *len1*: *length univ-qs* = *length qs*
using *assms*(*1*) **unfolding** *univariate-in-def*
by *auto*
have *len2*: *length reindexed-univ-qs* = *length univ-qs*
using *assms*(*2*) **by** *auto*
have *len*: *length reindexed-univ-qs* = *length qs*
using *len1 len2* **by** *auto*
have ⋀*i*. *i* < *length qs* ⟹ (*Polynomial.poly* (*eval-mpoly-poly xs* (*reindexed-univ-qs* ! *i*)) *x*) =
(*eval-mpoly* (*x*#*xs*) (*qs* ! *i*))
proof −

```
    fix i
    assume i < length qs
    have reindexed-univ-qs ! i =  (map-poly (lowerPoly 0 1)) ((univariate-in qs 0)
! i)
      using assms
      using ‹i < length qs› len1 by auto
    let ?q = (univariate-in qs 0) ! i
    let ?q1 = mpoly-to-mpoly-poly 0 (qs ! i)
    have ∀ c∈set (Polynomial.coeffs ?q1). 0 ∉ vars c
      using vars-coeff-mpoly-to-mpoly-poly[of 0 qs ! i]
      unfolding Polynomial.coeffs-def
      by auto
    then have ∀ c∈set (Polynomial.coeffs ?q). 0 ∉ vars c
      using multivar-as-univar
      by (metis ‹i < length qs› nth-map univariate-in-def)

    then show (Polynomial.poly (eval-mpoly-poly xs (reindexed-univ-qs ! i)) x) =
      (eval-mpoly (x#xs) (qs ! i))
      using univariate-in-eval lowering-poly-eval assms
      by (smt (verit, ccfv-SIG) ‹i < length qs› length-map nth-map)
  qed
  then show ?thesis
    using same len
    by (simp add: nth-map-conv)
qed

value variables-list [((Var 0 +(Const (3::real))*((Var 1)^2)):: real mpoly)]

value ((Var 0 +(Const (3::real))*((Var 1)^2)):: real mpoly)

value (mpoly-to-mpoly-poly-alt (1::nat) ((Var 0 +(Const (3::real))*((Var 1)^2))::
real mpoly))::
real mpoly Polynomial.poly


end


theory Multiv-Consistent-Sign-Assignments
  imports
    Multiv-Poly-Props
    Datatype-Order-Generator.Order-Generator

begin

derive linorder rat list
```

7 Define satisfies evaluation and proofs

definition *satisfies-evaluation-alternate*:: *real list* ⇒ *real mpoly* ⇒ *rat* ⇒ *bool*
where
satisfies-evaluation-alternate val f n =
(*sgn* (*eval-mpoly val f*) = *real-of-rat* (*sgn n*))

definition *satisfies-evaluation*:: *real list* ⇒ *real mpoly* ⇒ *rat* ⇒ *bool* **where**
satisfies-evaluation val f n =
((*Sturm-Tarski.sign* (*eval-mpoly val f*)::*real*) = (*Sturm-Tarski.sign n*::*real*))

lemma *satisfies-evaluation-alternate*:
shows *satisfies-evaluation-alternate val f n* = *satisfies-evaluation val f n*
proof −
have *h1*: *sgn* (*eval-mpoly val f*) = *real-of-rat* (*sgn n*) ⟹ *of-int* (*Sturm-Tarski.sign* (*eval-mpoly val f*)) = *of-int* (*Sturm-Tarski.sign n*)
by (*metis* (*no-types*, *lifting*) *Sturm-Tarski.sign-def of-rat-1 of-rat-eq-0-iff of-rat-eq-iff rel-simps*(*91*) *sgn-eq-0-iff sgn-if sign-simps*(*2*))
have *h2*: (*of-int*(*Sturm-Tarski.sign* (*eval-mpoly val f*))::*real*) = (*of-int*(*Sturm-Tarski.sign n*)::*real*) ⟹ *sgn* (*eval-mpoly val f*) = *real-of-rat* (*sgn n*)
by (*smt* (*verit*) *Sturm-Tarski.sign-def of-int-hom.injectivity of-rat-eq-0-iff of-rat-hom.hom-1-iff of-rat-neg-one sgn-if sign-simps*(*2*))
then show *?thesis* **unfolding** *satisfies-evaluation-alternate-def satisfies-evaluation-def*
using *h1 h2*
by *blast*
qed

lemma *eval-mpoly-poly-one-less-degree*:
assumes *satisfies-evaluation val* (*Polynomial.lead-coeff q*) *0*
shows *eval-mpoly-poly val* (*one-less-degree q*) =
eval-mpoly-poly val q
using *assms*
unfolding *one-less-degree-def satisfies-evaluation-def*
by (*metis assms diff-zero eval-mpoly-map-poly-comm-ring-hom.base.map-poly-hom-monom eval-mpoly-poly-comm-ring-hom.hom-minus eval-mpoly-poly-def monom-eq-0 of-rat-0 satisfies-evaluation-alternate satisfies-evaluation-alternate-def sgn-0-0*)

lemma *degree-valuation-le*:
shows *Polynomial.degree* (*eval-mpoly-poly val p*) ≤ *Polynomial.degree p*
unfolding *eval-mpoly-poly-def*
by (*simp add*: *degree-map-poly-le*)

lemma *satisfies-evaluation-nonzero*:
assumes *satisfies-evaluation val p n*
assumes *n* ≠ *0*
shows *eval-mpoly val p* ≠ *0*
using *assms* **unfolding** *satisfies-evaluation-def*
by (*smt* (*verit*, *ccfv-threshold*) *Sturm-Tarski.sign-def of-int-eq-iff*)

lemma *degree-valuation*:
assumes *satisfies-evaluation val* (*Polynomial.lead-coeff p*) *n*
assumes $n \neq 0$
shows *Polynomial.degree p* = *Polynomial.degree* (*eval-mpoly-poly val p*)
using *satisfies-evaluation-nonzero*[*OF assms*]
unfolding *eval-mpoly-poly-def satisfies-evaluation-def*
by (*metis Ring-Hom-Poly.degree-map-poly degree-0 eval-mpoly-map-poly-comm-ring-hom.hom-zero*)

lemma *lead-coeff-valuation*:
assumes *satisfies-evaluation val* (*Polynomial.lead-coeff p*) *n*
assumes $n \neq 0$
shows *eval-mpoly val* (*Polynomial.lead-coeff p*) =
Polynomial.lead-coeff (*eval-mpoly-poly val p*)
using *satisfies-evaluation-nonzero*[*OF assms*]
unfolding *eval-mpoly-poly-def satisfies-evaluation-def*
using *assms*(*1*) *assms*(*2*) *degree-valuation eval-mpoly-poly-def* **by** *force*

lemma *eval-commutes*:
fixes *p*:: *real mpoly Polynomial.poly*
assumes *eval-mpoly val* (*Polynomial.lead-coeff p*) ≠ *0*
shows *eval-mpoly val* (*Polynomial.lead-coeff p*) = *Polynomial.lead-coeff* (*eval-mpoly-poly val p*)
proof −
have (*Polynomial.degree p*) = (*Polynomial.degree* (*eval-mpoly-poly val p*))
using *assms*
using *degree-valuation satisfies-evaluation-def*
by (*metis degree-valuation-le eval-mpoly-map-poly-comm-ring-hom.base.coeff-map-poly-hom eval-mpoly-poly-def le-antisym le-degree*)
then have *eval-mpoly val* (*Polynomial.coeff p* (*Polynomial.degree p*)) = *Polynomial.coeff* (*eval-mpoly-poly val p*) (*Polynomial.degree* (*eval-mpoly-poly val p*))
using *assms lead-coeff-valuation satisfies-evaluation-def*
using *eval-mpoly-poly-coeff1 le-refl* **by** *presburger*
then show *?thesis*
by *auto*
qed

lemma *eval-mpoly-poly-pseudo-divmod*:
assumes *satisfies-evaluation val* (*Polynomial.lead-coeff p*) *n*
assumes $n \neq 0$
assumes *satisfies-evaluation val* (*Polynomial.lead-coeff q*) *m*
assumes $m \neq 0$
shows *pseudo-divmod* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*) =
(*map-prod* (*eval-mpoly-poly val*) (*eval-mpoly-poly val*) (*pseudo-divmod p q*))
proof −
from *satisfies-evaluation-nonzero*[*OF assms*(*3*−*4*)]
have *1*: *eval-mpoly-poly val q* ≠ *0* **using** *assms* **unfolding** *satisfies-evaluation-def*
by (*metis assms*(*3*−*4*) *lead-coeff-valuation leading-coeff-0-iff*)
then have *2*: *q* ≠ *0*

using *eval-mpoly-poly-def* **by** *fastforce*
show *?thesis* **unfolding** *pseudo-divmod-def*
using *1 2* **apply** *auto*
unfolding *eval-mpoly-poly-def*
by (*smt* (*verit*) *assms degree-valuation eval-mpoly-map-poly-comm-ring-hom.base.pseudo-divmod-main-hom eval-mpoly-poly-def lead-coeff-valuation leading-coeff-0-iff length-coeffs-degree map-poly-0 satisfies-evaluation-nonzero*)
qed

lemma *eval-mpoly-poly-pseudo-mod*:
assumes *satisfies-evaluation val* (*Polynomial.lead-coeff p*) *n*
assumes $n \neq 0$
assumes *satisfies-evaluation val* (*Polynomial.lead-coeff q*) *m*
assumes $m \neq 0$
shows *pseudo-mod* (*eval-mpoly-poly val p*)
(*eval-mpoly-poly val q*) =
eval-mpoly-poly val (*pseudo-mod p q*)
unfolding *pseudo-mod-def*
using *assms eval-mpoly-poly-pseudo-divmod* **by** *auto*

lemma *eval-mpoly-poly-smult*:
shows *Polynomial.smult* (*eval-mpoly val m*) (*eval-mpoly-poly val r*) =
eval-mpoly-poly val (*Polynomial.smult m r*)
apply (*intro poly-eqI*)
apply (*simp-all add*:*eval-mpoly-poly-def coeff-map-poly eval-mpoly-def*)
by (*simp add*: *insertion-mult*)

8 Consistent Sign Assignments for mpoly type

definition *mpoly-sign*:: *real list* ⇒ *real mpoly* ⇒ *rat* **where**
mpoly-sign val f = *of-int* (*Sturm-Tarski.sign* (*eval-mpoly val f*))

lemma *mpoly-sign-lemma-valuation-length*:
{*x*. ∃(*val*::*real list*). *mpoly-sign val q* = *x*} =
{*x*. ∃(*val*::*real list*). ((∀ *v* ∈ *vars q*. *length val* > *v*) ∧ *mpoly-sign val q* = *x*)}
proof −
have *subset1*: {*x*. ∃(*val*::*real list*). *mpoly-sign val q* = *x*}
⊆ {*x*. ∃(*val*::*real list*). ((∀ *v* ∈ *vars q*. *length val* > *v*) ∧ *mpoly-sign val q* = *x*)}
proof *clarsimp*
fix *val*::*real list*
{
assume ∗: (∀ *v*∈*vars q*. *v* < *length val*)
then have (∀ *v*∈*vars q*. *v* < *length val*) ∧ *mpoly-sign val q* = *mpoly-sign val q*
by *auto*
then have ∃ *vala*. (∀ *v*∈*vars q*. *v* < *length vala*) ∧ *mpoly-sign vala q* = *mpoly-sign val q*
by *auto*
}
moreover {

assume $*$: $(\exists\, v{\in}vars\ q.\ v \geq length\ val)$
have *finite* $\{vars\ q\}$
by *simp*
then have $\exists\, k.\ \forall\, v{\in}vars\ q.\ k > v$
by (*meson finite-nat-set-iff-bounded vars-finite*)
then obtain k **where** *k-prop*: $\forall\, v{\in}vars\ q.\ k > v$
by *auto*
then have *gtz*: $k - length\ val > 0$
using $*$ **by** *auto*
let *?app-len* $= k - length\ val$
have $\exists\,(l{::}real\ list).\ length\ l = ?app\text{-}len \wedge (\forall\, i < ?app\text{-}len.\ l\ !\ i = 0)$
using *gtz Polynomial.coeff-monom length-map length-upt nth-map*
proof −
{ fix *nn* :: *real list* ⇒ *nat*
{ assume $\exists\, r\ n\ na\ nb.\ nn\ (map\ (poly.coeff\ (Polynomial.monom\ r\ n))\ [na..{<}nb]) < nb - na \wedge nb - na = k - length\ val \wedge r = 0$
then have $\exists\, r\ n\ ns.\ nn\ (map\ (poly.coeff\ (Polynomial.monom\ r\ n))\ ns) < length\ ns \wedge length\ ns = k - length\ val \wedge r = 0$
by (*metis length-upt*)
then have $\exists\, rs.\ \neg\ nn\ rs < k - length\ val \vee length\ rs = k - length\ val \wedge rs\ !\ nn\ rs = 0$
by (*metis* (*no-types*) *Polynomial.coeff-monom length-map nth-map*) **}**
then have $\exists\, rs.\ \neg\ nn\ rs < k - length\ val \vee length\ rs = k - length\ val \wedge rs\ !\ nn\ rs = 0$
by *blast* **}**
then have $\exists\, rs.\ \forall\, n.\ \neg\ n < k - length\ val \vee length\ rs = k - length\ val \wedge rs\ !\ n = (0{::}real)$
by *meson*
then show *?thesis*
using *gtz* **by** *blast*
qed
then obtain *l*::*real list* **where** *l-prop*: $length\ l = ?app\text{-}len \wedge (\forall\, i < ?app\text{-}len.\ l\ !\ i = 0)$
by *auto*
let *?new-list* $=$ *append val l*
have *length ?new-list* $= k$ **using** *l-prop*
by (*metis add-diff-cancel-left' gtz length-append less-imp-add-positive zero-less-diff*)
then have *p1*: $\forall\, v{\in}vars\ q.\ v < length\ ?new\text{-}list$
using *k-prop*
by *meson*
have *p2*: *mpoly-sign ?new-list q* $=$ *mpoly-sign val q*
using *l-prop* **unfolding** *mpoly-sign-def eval-mpoly-def*
by (*smt* (*verit*, *best*) *insertion-irrelevant-vars nth-default-append nth-default-def*)

then have $\exists\, vala.\ (\forall\, v{\in}vars\ q.\ v < length\ vala) \wedge mpoly\text{-}sign\ vala\ q = mpoly\text{-}sign\ val\ q$
using *p1 p2*
by *blast*
}

ultimately have $\exists vala.\ (\forall v{\in}vars\ q.\ v < length\ vala) \wedge mpoly\text{-}sign\ vala\ q = mpoly\text{-}sign\ val\ q$
using *not-le-imp-less* **by** *blast*
then show $\exists vala.\ (\forall v{\in}vars\ q.\ v < length\ vala) \wedge mpoly\text{-}sign\ vala\ q = mpoly\text{-}sign\ val\ q$
by *blast*
qed
have *subset2*: $\{x.\ \exists(val{::}real\ list).\ ((\forall v \in vars\ q.\ length\ val > v) \wedge mpoly\text{-}sign\ val\ q = x)\}$
$\subseteq \{x.\ \exists(val{::}real\ list).\ mpoly\text{-}sign\ val\ q = x\}$
by *blast*
show *?thesis* **using** *subset1 subset2* **by** *auto*
qed

definition *map-mpoly-sign*::*real mpoly list* ⇒ *real list* ⇒ *rat list*
where *map-mpoly-sign qs val* ≡
map ((*rat-of-int* ∘ *Sturm-Tarski.sign*) ∘ (*eval-mpoly val*)) *qs*

definition *all-lists*:: *nat* ⇒ *real list set* **where**
all-lists n = {(*ls*::*real list*). *length ls* = *n*}

definition *mpoly-consistent-sign-vectors*::*real mpoly list* ⇒ *real list set* ⇒ *rat list set*
where *mpoly-consistent-sign-vectors qs S* = (*map-mpoly-sign qs*) ‘ *S*

definition *mpoly-csv*::*real mpoly list* ⇒ *rat list set*
where *mpoly-csv qs* = {*sign-vec*. (∃ *val*. *map-mpoly-sign qs val* = *sign-vec*)}

9 Data structure definitions

definition *mpoly-sign-data*:: *real list* ⇒ *real mpoly* ⇒ (*real mpoly* × *rat*) **where**
mpoly-sign-data val f = (*f*, *mpoly-sign val f*)

definition *map-mpoly-sign-data*:: *real list* ⇒ *real mpoly list* ⇒ (*real mpoly* × *rat*) *list* **where**
map-mpoly-sign-data val qs = *map* (λ*x*. *mpoly-sign-data val x*) *qs*

definition *mpoly-csv-data*::*real mpoly list* ⇒ (*real mpoly* × *rat*) *list set*
where *mpoly-csv-data qs* = {*sign-vec*. (∃ *val*. *map-mpoly-sign-data val qs* = *sign-vec*)}

definition *all-coeffs*:: *real mpoly Polynomial.poly list* ⇒ *real mpoly list*
where *all-coeffs qs* = *concat* (*map Polynomial.coeffs qs*)

primrec *all-coeffs-alt*:: *real mpoly Polynomial.poly list* ⇒ *real mpoly list*
where *all-coeffs-alt* [] = []
| *all-coeffs-alt* (*h*#*T*) = *append* (*Polynomial.coeffs h*) (*all-coeffs T*)

lemma *all-coeffs-alt*: *all-coeffs qs* = *all-coeffs-alt qs*
by (*metis* (*no-types*, *opaque-lifting*) *all-coeffs-alt.simps*(*1*) *all-coeffs-alt.simps*(*2*) *all-coeffs-def concat.simps*(*1*) *concat.simps*(*2*) *list.exhaust list.simps*(*8*) *list.simps*(*9*))

definition *all-coeffs-csv-data*::*real mpoly Polynomial.poly list* ⇒ (*real mpoly* × *rat*) *list set*
where *all-coeffs-csv-data qs* = *mpoly-csv-data* (*all-coeffs qs*)

primrec

lookup-assump-aux:: *'k* ⇒ (*'k* × *'a*) *list* ⇒ *'a option*
where *lookup-assump-aux p* [] = *None*
| *lookup-assump-aux p* (*h* # *T*) =
(*if* (*fst h* = *p*) *then Some* (*snd h*) *else lookup-assump-aux p T*)

fun *lookup-assump*:: *real mpoly* ⇒ (*real mpoly* × *rat*) *list* ⇒ *rat*
where *lookup-assump p q* = (*case* (*lookup-assump-aux p q*) *of*
None ⇒ *1000*
| *Some i* ⇒ *i*)

10 Lemmas about first nonzero coefficient helper

primrec *first-nonzero-coefficient-helper*:: (*real mpoly* × *rat*) *list* ⇒ *real mpoly list* ⇒ *rat*
where *first-nonzero-coefficient-helper assumps* [] = *0*
| *first-nonzero-coefficient-helper assumps* (*h* # *T*) =
(*case lookup-assump-aux h assumps of*
(*Some i*) ⇒ (*if i* ≠ *0 then i else first-nonzero-coefficient-helper assumps T*)
| *None* ⇒ *first-nonzero-coefficient-helper assumps T*)

definition *sign-of-first-nonzero-coefficient*:: (*real mpoly* × *rat*) *list* ⇒ *real mpoly Polynomial.poly* ⇒ *rat*
where *sign-of-first-nonzero-coefficient assumps q* = *first-nonzero-coefficient-helper assumps* (*rev* (*Polynomial.coeffs q*))

definition *sign-of-first-nonzero-coefficient-aux*:: (*real mpoly* × *rat*) *list* ⇒ *real mpoly list* ⇒ *rat*
where *sign-of-first-nonzero-coefficient-aux assumps coeffl* = *first-nonzero-coefficient-helper assumps coeffl*

lemma *sign-of-first-nonzero-coefficient-aux*:*sign-of-first-nonzero-coefficient-aux assumps* (*rev* (*Polynomial.coeffs q*)) = *sign-of-first-nonzero-coefficient assumps q*
by (*simp add*: *sign-of-first-nonzero-coefficient-aux-def sign-of-first-nonzero-coefficient-def*)

definition *sign-of-first-nonzero-coefficient-list*:: *real mpoly Polynomial.poly list* ⇒ (*real mpoly* × *rat*) *list* ⇒ *rat list*

where *sign-of-first-nonzero-coefficient-list qs assumps* = *map* (λ*q*. *sign-of-first-nonzero-coefficient assumps q*) *qs*

lemma *all-coeffs-member*:
fixes *qs*:: *real mpoly Polynomial.poly list*
fixes *q*:: *real mpoly Polynomial.poly*
fixes *coeff*:: *real mpoly*
assumes *q* ∈ *set qs*
assumes *inset*: *coeff* ∈ *set* (*Polynomial.coeffs q*)
shows *coeff* ∈ *set* (*all-coeffs qs*)
proof −
have *coeff* ∈ *set* (*all-coeffs qs*)
using *assms*
proof (*induction qs*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a qs*)
then show *?case*
by (*metis Un-iff all-coeffs-alt all-coeffs-alt.simps*(*2*) *set-ConsD set-append*)
qed
then show *?thesis* **using** *all-coeffs-alt* **by** *auto*
qed

lemma *map-mpoly-sign-data-duplicates*:
fixes *qs*:: *real mpoly list*
fixes *val*:: *real list*
fixes *coeff*:: *real mpoly*
shows ((*coeff*, *i*) ∈ *set* (*map-mpoly-sign-data val qs*) ∧ (*coeff*, *k*) ∈ *set* (*map-mpoly-sign-data val qs*)
⟹ *i* = *k*)
proof *clarsimp*
assume *m1*: (*coeff*, *i*) ∈ *set* (*map-mpoly-sign-data val qs*)
assume *m2*: (*coeff*, *k*) ∈ *set* (*map-mpoly-sign-data val qs*)
show *i* = *k*
using *m1 m2* **unfolding** *map-mpoly-sign-data-def mpoly-sign-data-def*
by (*smt* (*verit*, *del-insts*) *fst-conv imageE list.set-map snd-conv*)
qed

lemma *lookup-assump-aux-property*:
fixes *i*:: *rat*
fixes *l*:: (*real mpoly* × *rat*) *list*
assumes (*c*, *i*) ∈ *set l*
assumes *no-duplicates*: ∀ *j k*.
((*c*, *j*) ∈ *set l* ∧ (*c*, *k*) ∈ *set l* ⟶ *j* = *k*)
shows *lookup-assump-aux c l* = *Some i*
using *assms*
proof (*induct l*)
case *Nil*

then show *?case*
by *simp*
next
case (*Cons a l*)
then show *?case*
by *force*
qed

value *Polynomial.coeffs* ([:*1*, *2*, *3*:]::*real Polynomial.poly*)

lemma *lookup-assump-aux-eo*:
shows *lookup-assump-aux p assumps* = *None* ∨ (∃ *k*. *lookup-assump-aux p assumps* = *Some k*)
using *option.exhaust-sel* **by** *blast*

lemma *lookup-assump-means-inset*:
assumes *lookup-assump-aux p assumps* = *Some k*
shows (*p*, *k*) ∈ *set assumps*
using *assms* **proof** (*induct assumps*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a assumps*)
then show *?case*
by (*metis list.set-intros*(*1*) *list.set-intros*(*2*) *lookup-assump-aux.simps*(*2*) *option.inject prod.collapse*)
qed

lemma *inset-means-lookup-assump-some*:
assumes (*p*, *k*) ∈ *set assumps*
shows ∃ *j*. *lookup-assump-aux p assumps* = *Some j*
using *assms*
proof (*induct assumps*)
case *Nil*
then show *?case*
by *simp*
next
case (*Cons a assumps*)
then show *?case*
by *force*
qed

value *List.drop 2* [(*0*::*int*), *0*, *3*, *2*, *1*]

lemma *sign-of-first-nonzero-coefficient-drop*:
assumes *list-len* = *length ell*
assumes *k* < *list-len*
assumes ⋀*i*. ((*i* ≥ *k* ∧ *i* < *list-len*) ⟹ (*lookup-assump-aux* (*ell* ! *i*) *assumps* = *None* ∨ *lookup-assump-aux* (*ell* ! *i*) *assumps* = *Some 0*))

shows *first-nonzero-coefficient-helper assumps* (*rev ell*) = *first-nonzero-coefficient-helper assumps* (*drop* (*list-len* − *k*) (*rev ell*))
using *assms*
proof (*induct length ell arbitrary*: *ell list-len k*)
case *0*
then show *?case*
by *auto*
next
case (*Suc x*)
then have ∃ *sub-ell*. *ell* = *sub-ell* @[*nth ell* (*length ell* − *1*)]
by (*metis cancel-comm-monoid-add-class.diff-cancel diff-Suc-1 diff-is-0-eq lessI take-Suc-conv-app-nth take-all*)
then obtain *sub-ell* **where** *sub-ell*: *ell* = *sub-ell* @ [*nth ell* (*length ell* − *1*)] **by** *auto*
then have *len-sub-ell*: *length sub-ell* = *x*
by (*metis Suc.hyps*(*2*) *diff-Suc-1 length-append-singleton*)
have *rev-prop*: *rev ell* = (*nth ell* (*length ell* − *1*))#(*rev sub-ell*)
using *sub-ell*
by *simp*
then have *drop-prop*: (*drop* (*x* − (*k*−*1*)) (*rev sub-ell*)) = (*drop* (*x* − *k* + *2*) (*rev ell*))
by (*smt* (*verit*, *best*) *Suc.hyps*(*2*) *Suc.prems*(*1*) *Suc.prems*(*2*) *Suc-1 Suc-diff-Suc Suc-eq-plus1 add-diff-cancel-right add-diff-inverse-nat diff-Suc-1 diff-diff-left diff-is-0-eq drop-Suc-Cons drop-rev less-imp-le-nat less-one*)
then have *drop-prop2*: (*drop* (*x* − (*k*−*1*)) (*rev sub-ell*)) = (*drop* (*x* − *k* + *1*) (*drop 1* (*rev ell*)))
by *simp*
have ∃ *i*. (*i* ≥ *k* ∧ *i* < *list-len*) ⟶
lookup-assump-aux (*ell* ! *i*) *assumps* = *None* ∨ *lookup-assump-aux* (*ell* ! *i*) *assumps* = *Some 0*
using *Suc.prems*(*3*) **by** *presburger*
let *?i* = (*length ell* − *1*)
have *lookup-assump-aux* (*ell* ! *?i*) *assumps* = *None* ∨ *lookup-assump-aux* (*ell* ! *?i*) *assumps* = *Some 0*
using *assms*(*3*) *assms*(*2*)
by (*metis Suc.hyps*(*2*) *Suc.prems*(*1*) *Suc.prems*(*2*) *Suc.prems*(*3*) *diff-Suc-1 lessI linorder-not-le not-less-eq*)
then have *lookup-assump-aux* ((*rev ell*) ! *0*) *assumps* = *None* ∨ *lookup-assump-aux* ((*rev ell*) ! *0*) *assumps* = *Some 0*
using *rev-prop*
by (*metis nth-Cons-0*)
then have *key-prop*: *first-nonzero-coefficient-helper assumps* (*rev ell*) =
first-nonzero-coefficient-helper assumps (*drop 1* (*rev ell*))
unfolding *first-nonzero-coefficient-helper-def*
by (*smt* (*verit*, *ccfv-SIG*) *One-nat-def drop0 drop-Suc-Cons list.simps*(*7*) *nth-Cons-0 option.simps*(*4*) *option.simps*(*5*) *rev-prop*)
then have *key-prop2*: *first-nonzero-coefficient-helper assumps* (*rev ell*) =
first-nonzero-coefficient-helper assumps (*rev sub-ell*)
using *rev-prop*

```
    by (metis One-nat-def drop0 drop-Suc-Cons)
  have eo: k = length ell − 1 ∨ k < length sub-ell
    using len-sub-ell
    using Suc.hyps(2) Suc.prems(1) Suc.prems(2) by linarith
  moreover {
    assume ∗: k = length ell − 1
    then have len: list-len − k = 1
      using len-sub-ell Suc.prems(1) Suc.hyps(2)
      by simp
    then have first-nonzero-coefficient-helper assumps (rev ell) =
       first-nonzero-coefficient-helper assumps (drop (list-len − k) (rev ell))
      using key-prop by auto
  }
  moreover {
    assume ∗: k < length sub-ell
    have impl: x = length sub-ell ⟹
    k < length sub-ell ⟹
    (⋀i. k ≤ i ∧ i < length sub-ell ⟹
          lookup-assump-aux (sub-ell ! i) assumps = None ∨
          lookup-assump-aux (sub-ell ! i) assumps = Some 0) ⟹
    first-nonzero-coefficient-helper assumps (rev sub-ell) =
   first-nonzero-coefficient-helper assumps (drop ((length sub-ell) − k) (rev sub-ell))
      using Suc.prems Suc.hyps sub-ell
      by blast
    have ⋀i. (i ≥ k ∧ i < list-len) ⟹
     lookup-assump-aux (ell ! i) assumps = None ∨ lookup-assump-aux (ell ! i)
assumps = Some 0
      using Suc.prems(3) by auto
    then have sub-ell-prop: (⋀i. (i ≥ k ∧ i < (length sub-ell)) ⟹
          lookup-assump-aux (sub-ell ! i) assumps = None ∨
          lookup-assump-aux (sub-ell ! i) assumps = Some 0)
      using sub-ell
      by (metis Suc.hyps(2) Suc.prems(1) len-sub-ell less-SucI nth-append)
    then have first-nonzero-coefficient-helper assumps (rev sub-ell) =
   first-nonzero-coefficient-helper assumps (drop ((length sub-ell) − k) (rev sub-ell))
      using ∗ len-sub-ell sub-ell-prop impl
      by blast
    then have first-nonzero-coefficient-helper assumps (rev ell) =
       first-nonzero-coefficient-helper assumps (drop (list-len − k) (rev ell))
      using key-prop2 drop-prop2
        by (metis (full-types) Suc.hyps(2) Suc.prems(1) diff-Suc-1 diff-commute
drop-Cons′ len-sub-ell rev-prop)
    }
  ultimately have first-nonzero-coefficient-helper assumps (rev ell) =
       first-nonzero-coefficient-helper assumps (drop (list-len − k) (rev ell))
    using eo
    by fastforce
  then show ?case by auto
qed
```

value *Polynomial.coeffs* ([:*0*, *1*, *2*, *3*:]::*real Polynomial.poly*)
value *Polynomial.degree* ([:*0*, *1*, *2*, *3*:]::*real Polynomial.poly*)

lemma *helper-two*:
assumes *deg-gt*: *Polynomial.degree q* > *0*
assumes *sat-eval*: ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *lc-zero*: *lookup-assump-aux* (*Polynomial.lead-coeff q*) *assumps* = *Some 0*
shows *sign-of-first-nonzero-coefficient assumps q* = *sign-of-first-nonzero-coefficient assumps* (*one-less-degree q*)
proof −
let *?coeffs-q* = *Polynomial.coeffs q*
let *?coeffs-less* = *Polynomial.coeffs* (*one-less-degree q*)
obtain *r* **where** *r*:*Polynomial.degree q* = *Suc r*
using *deg-gt not0-implies-Suc*
by *blast*
from *poly-as-sum-of-monoms*[*of q*]
have *lc-is*: (*Polynomial.lead-coeff q*) = (*Polynomial.coeffs q*) ! (*r* + *1*)
using *r*
by (*metis Suc-eq-plus1 coeffs-nth deg-gt degree-0 le-refl less-numeral-extra*(*3*))
have *qis*: *q* = (∑ *i*≤*r*. *Polynomial.monom* (*poly.coeff q i*) *i*) + *Polynomial.monom* (*Polynomial.lead-coeff q*) (*Polynomial.degree q*)
using ‹(∑ *i*≤*Polynomial.degree q*. *Polynomial.monom* (*poly.coeff q i*) *i*) = *q*› *r* **by** *auto*
then have *oldis*: *q* − *Polynomial.monom* (*Polynomial.lead-coeff q*) (*Polynomial.degree q*) = (∑ *i*≤*r*. *Polynomial.monom* (*poly.coeff q i*) *i*)
using *diff-eq-eq* **by** *blast*
have *same-coeffs*: ∀ *i* ≤ *r*. *Polynomial.coeff q i* = *Polynomial.coeff* (*one-less-degree q*) *i*
using *qis oldis*
by (*metis* (*no-types*, *lifting*) *Multiv-Poly-Props.one-less-degree-def Orderings.order-eq-iff Polynomial.coeff-diff Polynomial.coeff-monom diff-zero not-less-eq-eq r*)
then have *coeff-zer*: ∀ *i* ≤ *r* . (*i* > (*length* (*Polynomial.coeffs* (*one-less-degree q*)) −*1*) ⟶ (*Polynomial.coeffs q*) ! *i* = *0*)
by (*metis coeffs-between-one-less-degree coeffs-nth deg-gt degree-0 degree-eq-length-coeffs le-imp-less-Suc nat-less-le r*)
then have ⋀*i*. (*i* < *r* + *1* ∧ *i* ≥ (*length* (*Polynomial.coeffs* (*one-less-degree q*)))) ⟹ (*lookup-assump-aux* ((*Polynomial.coeffs q*) ! *i*) *assumps* = *None* ∨ *lookup-assump-aux* ((*Polynomial.coeffs q*) ! *i*) *assumps* = *Some 0*)
proof −
fix *i*
let *?coeff* = (*Polynomial.coeffs q*) ! *i*
assume *i* < *r* + *1* ∧ *i* ≥ (*length* (*Polynomial.coeffs* (*one-less-degree q*)))
then have (*Polynomial.coeffs q*) ! *i* = *0* **using** *coeff-zer*
by (*metis* (*no-types*, *lifting*) *Multiv-Poly-Props.one-less-degree-def Polynomial.coeff-monom Suc-eq-plus1 add-diff-cancel-left' coeffs-eq-Nil coeffs-nth degree-0 diff-less diff-zero length-0-conv length-greater-0-conv less-Suc-eq-le less-imp-diff-less oldis order-le-less qis r*)

then have $\bigwedge k.$ *Polynomial.coeffs q* ! *i* = *0* $\Longrightarrow$ *k* $\neq$ *0* $\Longrightarrow$ (*0*, *k*) $\in$ *set assumps* $\Longrightarrow$ *False*
using *sat-eval* **unfolding** *satisfies-evaluation-def*
using *eval-mpoly-map-poly-comm-ring-hom.base.hom-zero sat-eval satisfies-evaluation-nonzero* **by** *blast*
then have $\neg(\exists\, k.\ k \neq 0 \wedge (?coeff, k) \in set\ assumps)$
by (*metis* ‹*Polynomial.coeffs q* ! *i* = *0*›)
then have $\neg(\exists\, k.\ k \neq 0 \wedge$ *lookup-assump-aux* ((*Polynomial.coeffs q*) ! *i*) *assumps* = *Some k*)
using *lookup-assump-means-inset*
by *metis*
then show (*lookup-assump-aux* ((*Polynomial.coeffs q*) ! *i*) *assumps* = *None* $\vee$ *lookup-assump-aux* ((*Polynomial.coeffs q*) ! *i*) *assumps* = *Some 0*)
using *lookup-assump-aux-eo*
by *metis*
qed
then have *lookup-inbtw*: $\bigwedge i.$ (*i* < *r* + *2* $\wedge$ *i* $\geq$ (*length* (*Polynomial.coeffs* (*one-less-degree q*)))) $\Longrightarrow$ (*lookup-assump-aux* ((*Polynomial.coeffs q*) ! *i*) *assumps* = *None* $\vee$ *lookup-assump-aux* ((*Polynomial.coeffs q*) ! *i*) *assumps* = *Some 0*)
using *lc-is lc-zero nat-less-le*
by (*metis Suc-1 add-Suc-right less-antisym*)
let *?ell* = (*Polynomial.coeffs q*)
let *?list-len* = *length ?ell*
let *?k* = (*length* (*Polynomial.coeffs* (*one-less-degree q*)))
have *sublist*: *Sublist.strict-prefix* (*Polynomial.coeffs* (*Multiv-Poly-Props.one-less-degree q*)) (*Polynomial.coeffs q*)
using *deg-gt one-less-degree-is-strict-prefix assms* **by** *auto*
then have *drop-is*: (*drop* (*?list-len* − *?k*) (*rev ?ell*)) = (*rev* (*Polynomial.coeffs* (*Multiv-Poly-Props.one-less-degree q*)))
using *same-coeffs one-less-degree-is-strict-prefix*
by (*metis append-eq-conv-conj deg-gt one-less-degree-is-prefix prefix-def rev-take*)

let *?full-list* = (*rev* (*Polynomial.coeffs q*))
let *?sub-list* = (*rev* (*Polynomial.coeffs* (*Multiv-Poly-Props.one-less-degree q*)))
have *length* (*Polynomial.coeffs q*) = *r* + *2*
using *r* **unfolding** *Polynomial.coeffs-def*
by *auto*
have *fnz*: *first-nonzero-coefficient-helper assumps* (*?full-list*) = *first-nonzero-coefficient-helper assumps* (*drop* (*length ?full-list* − *length ?sub-list*) (*?full-list*))
using *lookup-inbtw sign-of-first-nonzero-coefficient-drop*[*of r* + *2 Polynomial.coeffs q length ?sub-list assumps*]
by (*metis* ‹*length* (*Polynomial.coeffs q*) = *r* + *2*› *diff-is-0-eq drop0 length-rev linorder-not-le*)
have *?full-list* = *append* (*take* (*length ?full-list* − *length ?sub-list*) *?full-list*) *?sub-list*
using *sublist drop-is*
by (*metis append-take-drop-id length-rev*)
then have *first-nonzero-coefficient-helper assumps* (*rev* (*Polynomial.coeffs q*)) =

first-nonzero-coefficient-helper assumps
(rev (Polynomial.coeffs (Multiv-Poly-Props.one-less-degree q)))
using *fnz*
by (*simp add*: *drop-is*)
then show *?thesis*
unfolding *sign-of-first-nonzero-coefficient-def* **by** *auto*
qed

lemma *sign-fnz-aux-helper*:
assumes ∀ *elem*. *elem* ∈ *set coeffl* ⟶ *lookup-assump-aux elem ell* = *Some 0*
shows *sign-of-first-nonzero-coefficient-aux ell coeffl* = *0* **using** *assms*
proof (*induct coeffl*)
case *Nil*
then show *?case*
by (*simp add*: *sign-of-first-nonzero-coefficient-aux-def*)
next
case (*Cons a x*)
have *firsth*: *lookup-assump-aux a ell* = *Some 0*
using *Cons.prems*
by *auto*
have ∀ *elem*. *elem* ∈ *set x* ⟶ *lookup-assump-aux elem ell* = *Some 0*
using *Cons.prems*
by *auto*
then have *bigh*: *sign-of-first-nonzero-coefficient-aux ell x* = *0*
using *Cons.hyps* **by** *auto*
then have *first-nonzero-coefficient-helper ell x* = *0*
unfolding *sign-of-first-nonzero-coefficient-aux-def*
by *auto*
then show *?case* **using** *firsth* **unfolding** *sign-of-first-nonzero-coefficient-aux-def*
by *auto*
qed

lemma *sign-fnz-helper*:
assumes ∀ *coeff*. *coeff* ∈ *set* (*Polynomial.coeffs q*) ⟶ *lookup-assump-aux coeff* (*map-mpoly-sign-data val* (*all-coeffs qs*))
= *Some 0*
shows *sign-of-first-nonzero-coefficient* (*map-mpoly-sign-data val* (*all-coeffs qs*)) *q* = *0* **using** *assms*
proof −
have *sign-of-first-nonzero-coefficient-aux* (*map-mpoly-sign-data val* (*all-coeffs qs*)) (*rev* (*Polynomial.coeffs q*)) = *0*
using *sign-fnz-aux-helper*[*of* (*Polynomial.coeffs q*) (*map-mpoly-sign-data val* (*all-coeffs qs*))] *assms*
by (*metis set-rev sign-fnz-aux-helper*)
then show *?thesis* **using**
sign-of-first-nonzero-coefficient-aux **by** *auto*
qed

lemma *sign-of-first-nonzero-coefficient-zer*:

assumes *qin*: $q \in set\ qs$
assumes $(eval\text{-}mpoly\text{-}poly\ val\ q) = 0$
shows *sign-of-first-nonzero-coefficient* (*map-mpoly-sign-data val* (*all-coeffs qs*)) $q =$
Sturm-Tarski.sign (*Polynomial.lead-coeff* (*eval-mpoly-poly val q*))
proof −
have *st-zero*: *Sturm-Tarski.sign* (*Polynomial.lead-coeff* (*eval-mpoly-poly val q*)) $= 0$
using *assms*
by *simp*
have *h1*: $\bigwedge coeff.$
$q \in set\ qs \Longrightarrow$
$Poly\ (map\ (eval\text{-}mpoly\ val)\ (Polynomial.coeffs\ q)) = 0 \Longrightarrow$
$coeff \in set\ (Polynomial.coeffs\ q) \Longrightarrow 0 < eval\text{-}mpoly\ val\ coeff \Longrightarrow False$
by (*metis* (*no-types*, *opaque-lifting*) *Poly-eq-0 image-eqI image-set in-set-replicate less-numeral-extra*(*3*))
have *h2*: $\bigwedge coeff.$
$q \in set\ qs \Longrightarrow$
$Poly\ (map\ (eval\text{-}mpoly\ val)\ (Polynomial.coeffs\ q)) = 0 \Longrightarrow$
$coeff \in set\ (Polynomial.coeffs\ q) \Longrightarrow$
$\neg\ 0 < eval\text{-}mpoly\ val\ coeff \Longrightarrow eval\text{-}mpoly\ val\ coeff = 0$
by (*metis* (*no-types*, *opaque-lifting*) *Poly-eq-0 image-eqI image-set in-set-replicate*)
have *coeff-zero*: $\forall\ coeff \in set\ (Polynomial.coeffs\ q).\ mpoly\text{-}sign\ val\ coeff = 0$
using *assms* **unfolding** *eval-mpoly-poly-def map-poly-def mpoly-sign-def*
using *h1 h2* **using** *sign-simps*(*2*) **by** *blast*
have $\forall\ coeff \in set\ (Polynomial.coeffs\ q).\ lookup\text{-}assump\text{-}aux\ coeff\ (map\text{-}mpoly\text{-}sign\text{-}data\ val\ (all\text{-}coeffs\ qs))$
$= Some\ 0$
proof *clarsimp*
fix *coeff*
assume *inset*: $coeff \in set\ (Polynomial.coeffs\ q)$
then have *h1*: $mpoly\text{-}sign\ val\ coeff = 0$
using *coeff-zero* **by** *auto*
have *h2*: $coeff \in set\ (all\text{-}coeffs\ qs)$
using *qin inset all-coeffs-member all-coeffs-alt*
by *blast*
have $(coeff, 0) \in set\ (map\text{-}mpoly\text{-}sign\text{-}data\ val\ (all\text{-}coeffs\ qs))$
unfolding *map-mpoly-sign-data-def mpoly-sign-data-def*
using *h1 h2*
by (*simp add*: *list.set-map*)
then show $lookup\text{-}assump\text{-}aux\ coeff\ (map\text{-}mpoly\text{-}sign\text{-}data\ val\ (all\text{-}coeffs\ qs)) = Some\ 0$
using *lookup-assump-aux-property map-mpoly-sign-data-duplicates* **by** *presburger*
qed
then have $\forall\ coeff.\ coeff \in set\ (Polynomial.coeffs\ q) \longrightarrow lookup\text{-}assump\text{-}aux\ coeff\ (map\text{-}mpoly\text{-}sign\text{-}data\ val\ (all\text{-}coeffs\ qs))$
$= Some\ 0$
by *simp*

then show *?thesis* **using** *st-zero sign-fnz-helper*
by *simp*
qed

lemma *sign-of-first-nonzero-coefficient-nonzer*:
assumes *inset*: $q \in set\ qs$
assumes *nonz*: $(eval\text{-}mpoly\text{-}poly\ val\ q) \neq 0$
assumes *sat-eval*: $\bigwedge p\ n.\ (p,n) \in set\ (map\text{-}mpoly\text{-}sign\text{-}data\ val\ (all\text{-}coeffs\ qs)) \Longrightarrow satisfies\text{-}evaluation\ val\ p\ n$
shows $sign\text{-}of\text{-}first\text{-}nonzero\text{-}coefficient\ (map\text{-}mpoly\text{-}sign\text{-}data\ val\ (all\text{-}coeffs\ qs))\ q =$
$Sturm\text{-}Tarski.sign\ (Polynomial.lead\text{-}coeff\ (eval\text{-}mpoly\text{-}poly\ val\ q))$
proof −
let *?assumps* = $(map\text{-}mpoly\text{-}sign\text{-}data\ val\ (all\text{-}coeffs\ qs))$
have *qnonz*: $q \neq 0$ **using** *nonz* **by** *auto*
let *?eval-q* = $(eval\text{-}mpoly\text{-}poly\ val\ q)$
have $\forall x > (Polynomial.degree\ ?eval\text{-}q).\ Polynomial.coeff\ ?eval\text{-}q\ x = 0$
using *coeff-eq-0* **by** *blast*
have *deg-leq*: $(Polynomial.degree\ ?eval\text{-}q) \leq Polynomial.degree\ q$
by (*simp add*: *degree-map-poly-le eval-mpoly-poly-def*)
let *?deg-eq* = *Polynomial.degree ?eval-q*
let *?deg-q* = *Polynomial.degree q*
have *st-nonzero*: $Sturm\text{-}Tarski.sign\ (Polynomial.lead\text{-}coeff\ ?eval\text{-}q) \neq 0$
using *nonz*
by (*simp add*: *Sturm-Tarski.sign-def*)
then have *coi-sign*: $mpoly\text{-}sign\ val\ (Polynomial.coeff\ q\ ?deg\text{-}eq) = Sturm\text{-}Tarski.sign\ (Polynomial.lead\text{-}coeff\ ?eval\text{-}q)$
unfolding *mpoly-sign-def eval-mpoly-poly-def*
by *auto*
let *?coi* = *Polynomial.coeff q ?deg-eq*
have *mem*: $((mpoly\text{-}sign\text{-}data\ val\ ?coi)::real\ mpoly \times rat) \in set\ ?assumps$
unfolding *map-mpoly-sign-data-def* **using** *all-coeffs-member*[*of q qs ?coi*]
by (*metis* ‹*Polynomial.degree* (*eval-mpoly-poly val q*) ≤ *Polynomial.degree q*› *coeff-in-coeffs eval-mpoly-poly-comm-ring-hom.hom-zero image-eqI image-set inset nonz*)
then obtain *elem1 elem2* **where** *elems-prop*: $(elem1, elem2) = mpoly\text{-}sign\text{-}data\ val\ ?coi$
using *mpoly-sign-data-def* **by** *force*
then have *elem2-prop*: $elem2 = Sturm\text{-}Tarski.sign\ (Polynomial.lead\text{-}coeff\ ?eval\text{-}q)$
using *coi-sign*
by (*simp add*: *mpoly-sign-data-def*)
have *key1*: $lookup\text{-}assump\text{-}aux\ ?coi\ ?assumps = Some\ (rat\text{-}of\text{-}int\ (Sturm\text{-}Tarski.sign\ (Polynomial.lead\text{-}coeff\ ?eval\text{-}q)))$
using *sat-eval elems-prop mem elem2-prop st-nonzero*
by (*simp add*: *eval-mpoly-poly-coeff1 lookup-assump-aux-property map-mpoly-sign-data-duplicates mpoly-sign-data-def mpoly-sign-def*)
have *len-coeffs-q*: $length\ (Polynomial.coeffs\ q) = ?deg\text{-}q + 1$
unfolding *Polynomial.coeffs-def* **using** *qnonz*
by *simp*

```
  have len-coeffs-eq: length (Polynomial.coeffs ?eval-q) = ?deg-eq + 1
    using length-coeffs nonz by blast
  moreover {
    assume *: (Polynomial.degree ?eval-q) = Polynomial.degree q
    then have coi-is: ?coi = Polynomial.lead-coeff q
      by simp
    have ∃ h T. (rev (Polynomial.coeffs q)) = (h#T)
      by (meson neq-Nil-conv not-0-coeffs-not-Nil qnonz rev-is-Nil-conv)
    then obtain h T where ht-prop: (rev (Polynomial.coeffs q)) = (h#T)
      by auto
   have (rev (Polynomial.coeffs q)) ! 0 = (Polynomial.coeffs q) ! (Polynomial.degree
q)
      by (simp add: degree-eq-length-coeffs qnonz rev-nth)
    then have revis: (rev (Polynomial.coeffs q)) ! 0 = ?coi
      using coi-is
      by (simp add: coeffs-nth qnonz)
     then have lookup-assump-aux ((rev (Polynomial.coeffs q)) ! 0) ?assumps =
Some (rat-of-int (Sturm-Tarski.sign (Polynomial.lead-coeff ?eval-q)))
      using key1 st-nonzero coi-sign revis
    unfolding sign-of-first-nonzero-coefficient-def first-nonzero-coefficient-helper-def
      by auto
    then have ?thesis
      using ht-prop st-nonzero unfolding sign-of-first-nonzero-coefficient-def
      by auto
  }
  moreover {
    assume *: (Polynomial.degree ?eval-q) < Polynomial.degree q
   then have lt: Polynomial.degree (eval-mpoly-poly val q) + 1 < Polynomial.degree
q + 1
      using len-coeffs-q len-coeffs-eq add-less-cancel-right by blast
    have key2: ⋀x. ((x ≥ ?deg-eq + 1 ∧ x < ?deg-q + 1) ⟹
      lookup-assump-aux ((Polynomial.coeffs q) ! x) ?assumps = Some 0)
    proof −
      fix x
      assume xgeq: (x ≥ ?deg-eq + 1 ∧ x < ?deg-q + 1)
      let ?coi2 = ((Polynomial.coeffs q) ! x)
      have mem: ((mpoly-sign-data val ?coi2)::real mpoly × rat) ∈ set ?assumps
        unfolding map-mpoly-sign-data-def using all-coeffs-member[of q qs ?coi2]
        by (metis image-eqI image-set inset len-coeffs-q nth-mem xgeq)
    then obtain newelem2 where newelems-prop: (?coi2, newelem2) = mpoly-sign-data
val ?coi2
        using mpoly-sign-data-def by force
      have xzer: eval-mpoly val ?coi2 = 0
        using xgeq
     by (metis Suc-eq-plus1 coeff-eq-0 coeffs-nth eval-mpoly-map-poly-comm-ring-hom.base.coeff-map-poly-hom
eval-mpoly-poly-def linorder-not-le not-less-eq-eq qnonz)
      have elem2-prop: (sgn (eval-mpoly val ?coi2) = real-of-rat (sgn newelem2))
        using sat-eval[of ?coi2 newelem2] mem newelems-prop
      using satisfies-evaluation-alternate unfolding satisfies-evaluation-alternate-def
```

satisfies-evaluation-def
by *metis*
then have *key11*: *lookup-assump-aux ?coi2 ?assumps = Some 0*
using *xzer*
by (*metis lookup-assump-aux-property map-mpoly-sign-data-duplicates mem newelems-prop of-rat-0 of-rat-hom.injectivity sgn-0-0*)
then show *lookup-assump-aux* ((*Polynomial.coeffs q*) ! *x*) *?assumps = Some 0* **by** *auto*
qed
then have (⋀*i*. *Polynomial.degree* (*eval-mpoly-poly val q*) + *1* ≤ *i* ∧ *i* < *Polynomial.degree q* + *1* ⟹
lookup-assump-aux (*Polynomial.coeffs q* ! *i*) *?assumps = None* ∨
lookup-assump-aux (*Polynomial.coeffs q* ! *i*) *?assumps = Some 0*)
by *blast*
then have *fnz*: *first-nonzero-coefficient-helper ?assumps* (*rev* (*Polynomial.coeffs q*))
= *first-nonzero-coefficient-helper ?assumps* (*drop* ((*?deg-q* + *1*) − (*?deg-eq* + *1*)) (*rev* (*Polynomial.coeffs q*)))
using *sign-of-first-nonzero-coefficient-drop*[*of ?deg-q* + *1 Polynomial.coeffs q ?deg-eq* + *1 ?assumps*]
using *len-coeffs-q lt* **by** *auto*
have *coeff-deg-eq*: (*Polynomial.coeffs q*) ! *?deg-eq = ?coi*
unfolding *Polynomial.coeffs-def*
by (*smt* (*verit*, *ccfv-threshold*) *Polynomial.coeffs-def coeffs-nth deg-leq qnonz*)
have (*Polynomial.coeffs q*) ! *?deg-eq* = (*Polynomial.coeff q ?deg-eq*)
unfolding *Polynomial.coeffs-def*
by (*smt* (*verit*, *ccfv-SIG*) *Polynomial.coeffs-def coeff-deg-eq*)
then have *drop-zer-is*: (*drop* (*?deg-q* − *?deg-eq*) (*rev* (*Polynomial.coeffs q*))) ! *0* = (*Polynomial.coeff q ?deg-eq*)
using *len-coeffs-q*
by (*metis* (*no-types*, *lifting*) *add.right-neutral add-Suc-right deg-leq degree-eq-length-coeffs diff-diff-cancel diff-diff-left diff-le-self diff-less-Suc length-rev nth-drop plus-1-eq-Suc rev-nth*)
let *?loi* = (*drop* (*?deg-q* − *?deg-eq*) (*rev* (*Polynomial.coeffs q*)))
have ∃ *h T*. *?loi* = *h*#*T*
by (*metis Suc-eq-plus1 append.right-neutral append-take-drop-id diff-is-0-eq diff-less-Suc diff-less-mono le-refl len-coeffs-q length-rev length-take less-nat-zero-code min.cobounded2 variables.cases*)
then have *first-nonzero-coefficient-helper ?assumps* (*drop* ((*?deg-q* + *1*) − (*?deg-eq* + *1*)) (*rev* (*Polynomial.coeffs q*))) =
(*Sturm-Tarski.sign* (*Polynomial.lead-coeff ?eval-q*))
using *key1 st-nonzero drop-zer-is* **unfolding** *first-nonzero-coefficient-helper-def*

by *auto*
then have *?thesis* **unfolding** *sign-of-first-nonzero-coefficient-def*
using *fnz*
by *auto*
}
ultimately have *?thesis*

using *deg-leq nat-less-le* **by** *blast*
then show *?thesis* **by** *auto*
qed

lemma *sign-of-first-nonzero-coefficient*:
assumes *inset*: $q \in set\ qs$
assumes *sat-eval*: $\bigwedge p\ n.\ (p,n) \in set\ (map\text{-}mpoly\text{-}sign\text{-}data\ val\ (all\text{-}coeffs\ qs)) \Longrightarrow satisfies\text{-}evaluation\ val\ p\ n$
shows $sign\text{-}of\text{-}first\text{-}nonzero\text{-}coefficient\ (map\text{-}mpoly\text{-}sign\text{-}data\ val\ (all\text{-}coeffs\ qs))\ q =$
$Sturm\text{-}Tarski.sign\ (Polynomial.lead\text{-}coeff\ (eval\text{-}mpoly\text{-}poly\ val\ q))$
using *assms sign-of-first-nonzero-coefficient-zer sign-of-first-nonzero-coefficient-nonzer*
by *blast*

11 Relating multiple definitions

lemma *csv-as-expected-left*:
fixes *qs*:: *real mpoly list*
assumes *n-is*: $n = length\ (variables\text{-}list\ qs)$
assumes *biggest-var-is*: $biggest\text{-}var = nth\ (variables\text{-}list\ qs)\ (n-1) + 1$

assumes *qs-signs*: $qs\text{-}signs = mpoly\text{-}consistent\text{-}sign\text{-}vectors\ qs\ (all\text{-}lists\ biggest\text{-}var)$
shows $(sign\text{-}val \in qs\text{-}signs) \Longrightarrow (\exists\ val.\ (map\ (rat\text{-}of\text{-}int \circ Sturm\text{-}Tarski.sign \circ (\lambda p.\ eval\text{-}mpoly\ val\ p))\ qs = sign\text{-}val))$
proof −
assume *inset*: $sign\text{-}val \in qs\text{-}signs$
have $\exists (l::real\ list).\ (List.length\ l = biggest\text{-}var \wedge sign\text{-}val = map\text{-}mpoly\text{-}sign\ qs\ l)$
using *inset qs-signs* **unfolding** *mpoly-consistent-sign-vectors-def all-lists-def*
by *blast*
then show $(\exists\ val.\ (map\ (rat\text{-}of\text{-}int \circ Sturm\text{-}Tarski.sign \circ (\lambda p.\ eval\text{-}mpoly\ val\ p))\ qs = sign\text{-}val))$
using *map-mpoly-sign-def* **by** *auto*
qed

lemma *in-list-lemma*:
assumes $n = length\ l$
shows *inlist*: $(v \in set\ l \Longrightarrow (\exists\, k{\leq}n-1.\ v = nth\ l\ k))$
using *assms*
proof (*induct l arbitrary*: *n v*)
case *Nil*
then show *?case*
by *auto*
next
case (*Cons a l*)
then have $n - 1 = length\ l$
by *simp*
then have *ex-l*: $v \in set\ l \longrightarrow (\exists\, k{\leq}n-2.\ v = l\ !\ k)$
using *Cons.hyps*

```
    by (metis diff-diff-left one-add-one)
  have eo: v ∈ set (a#l) ⟹ v = a ∨ v ∈ set l
    by auto
  show ?case
  proof −
    have h1: v = a ⟹ ∃k≤n − Suc 0. v = (a # l) ! k
      by auto
    have h2: v ∈ set l ⟹ ∃k≤n − Suc 0. v = (a # l) ! k
    proof −
      assume ∗: v ∈ set l
      then have (∃k≤n−2. v = l ! k)
        using ex-l
        by (metis nat-1-add-1 plus-1-eq-Suc)
      then obtain k where k ≤ n − 2 ∧ v = l ! k
        by auto
      then have l ! k = (a # l) ! (k+1)
        by force
      then show ∃k≤n − Suc 0. v = (a # l) ! k
          by (metis ∗ One-nat-def Suc-leI ‹n − 1 = length l› in-set-conv-nth
nth-Cons-Suc)
    qed
    show ?thesis
      using h1 h2 Cons
      by (metis One-nat-def eo)
  qed
qed

lemma eval-list-longer-than-degree:
  assumes gt-than: ∀ i ∈ vars q. length val > i
  assumes length ell ≥ length val
  assumes ∀ i < length val. ell ! i = val ! i
  shows eval-mpoly ell q = eval-mpoly val q
proof −
  have ⋀m. lookup (mapping-of q) m ≠ 0 ⟹ (∏ v. nth-default 0 ell v ^ lookup
m v) = (∏ v. nth-default 0 val v ^ lookup m v)
  proof −
    fix m
    assume ∗: lookup (mapping-of q) m ≠ 0
    then have ∀ v. (lookup m v ≠ 0 ⟶ v ∈ vars q)
      by (metis coeff-def coeff-isolate-variable-sparse isovarsparNotIn)
    then have zer-lookup: ∀ v ≥ length val. lookup m v = 0
      using ∗ assms
      using linorder-not-less by blast
    have h1: ∀ v ≥ length val. nth-default 0 ell v ^ lookup m v = 1
      using zer-lookup by auto
    have h2: ∀ v ≥ length val. nth-default 0 val v ^ lookup m v = 1
      using zer-lookup by auto
    have h3: ∀ v < length val. nth-default 0 ell v ^ lookup m v = nth-default 0 val
v ^ lookup m v
```

```
    using assms
    by (metis nth-default-def order-less-le-trans)
  then show (∏ v. nth-default 0 ell v ^ lookup m v) = (∏ v. nth-default 0 val v
^ lookup m v)
    using h1 h2 h3
    by (metis linorder-not-le)
 qed
 then show ?thesis
  using assms unfolding eval-mpoly-def unfolding insertion-def insertion-aux-def
   unfolding insertion-fun-def
    by (smt (verit, best) Prod-any.cong Sum-any.cong id-apply map-fun-apply
mult-cancel-left)
qed

lemma same-eval-list-tailing-zeros:
 assumes length ell > length val
 assumes ∀ i < length val. ell ! i = val ! i
 assumes ell-zeros: ∀ i < length ell. (i ≥ length val ⟶ ell ! i = 0)
 shows eval-mpoly ell q = eval-mpoly val q
proof −
 have ⋀m. lookup (mapping-of q) m ≠ 0 ⟹ (∏ v. nth-default 0 ell v ^ lookup
m v) = (∏ v. nth-default 0 val v ^ lookup m v)
 proof −
  fix m
  assume lookup (mapping-of q) m ≠ 0
  have h1-val: ∀ v ≥ length val. nth-default 0 val v = 0
   by (simp add: nth-default-beyond)
  have h1-ell: ⋀ v . v ≥ length val ⟹ nth-default 0 ell v = 0
   by (simp add: ell-zeros nth-default-eq-dflt-iff)
  have h1: ∀ v ≥ length val. nth-default 0 ell v ^ lookup m v = nth-default 0 val
v ^ lookup m v
   using h1-val h1-ell
   by presburger
  have h2: ∀ v < length val. nth-default 0 ell v ^ lookup m v = nth-default 0 val
v ^ lookup m v
   using assms
   by (metis nth-default-nth order-less-trans)
  then show (∏ v. nth-default 0 ell v ^ lookup m v) = (∏ v. nth-default 0 val v
^ lookup m v)
   using h1 h2
   by (metis linorder-not-le)
 qed
 then show ?thesis
  using assms unfolding eval-mpoly-def unfolding insertion-def insertion-aux-def
   unfolding insertion-fun-def
    by (smt (verit, best) Prod-any.cong Sum-any.cong id-apply map-fun-apply
mult-cancel-left)
qed
```

lemma *biggest-variable-in-sorted-list*:
assumes *length-nonz*: *variables-list qs* ≠ []
assumes *n-is*: *n* = *length* (*variables-list qs*)
shows (*m* ∈ *set* (*variables-list qs*) ⟹ (*nth* (*variables-list qs*) (*n*−*1*)) ≥ *m*)
proof −
have *allk*: ∀ *k* < *n*−*1*. (*nth* (*variables-list qs*) *k*) ≤ (*nth* (*variables-list qs*) (*k*+*1*))
using *n-is*
by (*simp add*: *sorted-wrt-nth-less*)
then have ⋀*v*. ∀ *k*<*n* − *Suc 0*. *sorted-list-of-set* (*variables qs*) ! *k* ≤ *sorted-list-of-set* (*variables qs*) ! *Suc k* ⟹
(⋀*n l v*. *n* = *length l* ⟹ *v* ∈ *set l* ⟹ ∃ *k*≤*n* − *Suc 0*. *v* = *l* ! *k*) ⟹
v ∈ *set* (*sorted-list-of-set* (*variables qs*)) ⟹
v ≤ *sorted-list-of-set* (*variables qs*) ! (*n* − *Suc 0*)
by (*metis One-nat-def Suc-less-eq Suc-pred diff-less in-list-lemma length-greater-0-conv length-nonz less-numeral-extra*(*1*) *n-is sorted-iff-nth-Suc sorted-nth-mono variables-list.simps*)

then have *allin*: ∀ *v*. (*v* ∈ *set* (*variables-list qs*) ⟶ *v* ≤ *nth* (*variables-list qs*) (*n*−*1*))
using *inlist allk*
by (*auto*)
then show ⋀ *m*. (*m* ∈ *set* (*variables-list qs*) ⟹ (*nth* (*variables-list qs*) (*n*−*1*)) ≥ *m*)
proof −
fix *m*
assume *mem*: *m* ∈ *set* (*variables-list qs*)
let *?len* = *length* (*variables-list qs*)
have ∃ *w* < *?len*. *m* = (*variables-list qs*) ! *w*
using *mem*
by (*metis in-set-conv-nth*)
then obtain *w* **where** *w-prop*: *w* < *?len* ∧*m* = (*variables-list qs*) ! *w*
by *auto*
then have *leq*: *w* ≤ *n*−*1* **using** *n-is*
by *auto*
have *sorted* (*variables-list qs*)
using *sorted-sorted-list-of-set*
by *simp*
then show *nth* (*variables-list qs*) (*n*−*1*) ≥ *m*
using *leq w-prop allin mem*
by *blast*
qed
qed

lemma *csv-as-expected-right*:
fixes *qs*:: *real mpoly list*
assumes *length-nonz*: *length* (*variables-list qs*) > *0*
assumes *n-is*: *n* = *length* (*variables-list qs*)
assumes *biggest-var-is*: *biggest-var* = *nth* (*variables-list qs*) (*n*−*1*) + *1*

assumes *qs-signs*: *qs-signs* = *mpoly-consistent-sign-vectors qs* (*all-lists biggest-var*)

shows ($\exists$ *val*. (*map* (*rat-of-int* $\circ$ *Sturm-Tarski.sign* $\circ$ (λ*p*. *eval-mpoly val p*)) *qs* = *sign-val*)) $\Longrightarrow$ (*sign-val* $\in$ *qs-signs*)
proof −
assume ($\exists$ *val*. (*map* (*rat-of-int* $\circ$ *Sturm-Tarski.sign* $\circ$ (λ*p*. *eval-mpoly val p*)) *qs* = *sign-val*))
then obtain *val* **where** *val-prop*: (*map* (*rat-of-int* $\circ$ *Sturm-Tarski.sign* $\circ$ (λ*p*. *eval-mpoly val p*)) *qs* = *sign-val*)
by *auto*
then have *length sign-val* = *length qs*
using *List.length-map* **by** *auto*
have *inlist*: $\forall$ *v*. (*v* $\in$ *set* (*variables-list qs*) $\longrightarrow$ ($\exists$ *k*$\leq$*n*−*1*. *v* = *nth* (*variables-list qs*) *k*))
using *in-list-lemma n-is*
by *metis*
have *allin*: $\forall$ *v*. (*v* $\in$ *set* (*variables-list qs*) $\longrightarrow$ *v* $\leq$ *nth* (*variables-list qs*) (*n*−*1*))
using *inlist*
by (*metis biggest-variable-in-sorted-list length-nonz less-numeral-extra*(*3*) *list.size*(*3*) *n-is*)
have *sorted-list-of-set* (*variables qs*) = *remdups* (*sorted-list-of-set* (*variables qs*))
by (*metis remdups-id-iff-distinct sorted-list-of-set*(*3*))
then have *remdups*: *variables-list qs* = *remdups* (*variables-list qs*)
by *simp*
have (*nth* (*variables-list qs*) (*n*−*1*)) $\in$ *set* (*variables-list qs*)
using *n-is length-nonz*
by (*metis Suc-pred′ in-set-conv-nth lessI*)

then have *biggest*: $\bigwedge$ *m*. (*m* $\in$ *set* (*variables-list qs*) $\Longrightarrow$ (*nth* (*variables-list qs*) (*n*−*1*)) $\geq$ *m*)
using *assms biggest-variable-in-sorted-list*
using *allin* **by** *presburger*
have *gtthan-to-zero*: $\forall$ *m* $\geq$ *biggest-var*. $\forall$ (*q*::*real mpoly*) $\in$ *set*(*qs*). *MPoly-Type.degree* (*q*::*real mpoly*) *m* = *0*
proof *clarsimp*
fix *m q*
assume *m*: *biggest-var* $\leq$ *m*
assume *qin*: *q* $\in$ *set qs*
have $\forall$ *v*. (*v* $\in$ *set* (*variables-list qs*) $\longrightarrow$ *m* > *v*)
using *biggest m*
using *biggest-var-is* **by** *fastforce*
then have $\forall$ *v* $\in$ *vars q*. *m* > *v*
using *qin variables-list-prop*
by *blast*
then show *MPoly-Type.degree q m* = *0*
using *biggest-var-is n-is degree-eq-0-iff*
by *blast*
qed

moreover {
assume $*$: *length val* $\geq$ *biggest-var*

let *?ell = take biggest-var val*
have *ell-prop*: *length ?ell = biggest-var*
by (*simp add*: ∗)
have ⋀(*q*::*real mpoly*). *q*∈ *set qs* ⟹ *eval-mpoly ?ell q = eval-mpoly val q*
proof − **fix** *q*
assume *q* ∈ *set* (*qs*)
have *h1*: ∀ *i*∈*vars q*. *i* < *length* (*take biggest-var val*)
by (*metis* ‹*q* ∈ *set qs*› *degree-eq-0-iff ell-prop gtthan-to-zero linorder-le-less-linear*)
have *h2*: *length* (*take biggest-var val*) ≤ *length val*
using ∗ *ell-prop* **by** *auto*
have *h3*: ∀ *i*<*length* (*take biggest-var val*). *val* ! *i* = *take biggest-var val* ! *i*
by *simp*
show *eval-mpoly ?ell q = eval-mpoly val q*
using *h1 h2 h3 eval-list-longer-than-degree*[*of q ?ell val*]
by *auto*
qed
then have *map* (*rat-of-int* ∘ *Sturm-Tarski.sign* ∘ *eval-mpoly ?ell*) *qs* = *map* (*rat-of-int* ∘ *Sturm-Tarski.sign* ∘ *eval-mpoly val*) *qs*
by *auto*
then have ∃ *ell*. *length ell* = *biggest-var* ∧ *map* (*rat-of-int* ∘ *Sturm-Tarski.sign* ∘ *eval-mpoly ell*) *qs* = *sign-val*
using *ell-prop val-prop*
by *blast*
}
moreover {
assume ∗: *length val* < *biggest-var*
let *?ell* = *val* @ (*zero-list* (*biggest-var* − *length val*))
have *len*: *length ?ell* = *biggest-var*
using ∗ *zero-list-len*
by (*metis add-diff-cancel-left' eq-diff-iff length-append less-or-eq-imp-le zero-less-diff*)

then have *p1*: (∀ *n* < *length val*. *?ell* ! *n* = *val* ! *n*)
using ∗
by (*meson nth-append*)
have *p2*: (∀ *n* ≥ *length val*. *n* < *biggest-var* ⟶ *?ell* ! *n* = *0*)
using ∗ *zero-list-member*
by (*metis diff-less-mono leD nth-append*)
have ⋀*q*. (*q*::*real mpoly*) ∈ *set*(*qs*) ⟹ *eval-mpoly ?ell q = eval-mpoly val q*
proof −
fix *q*
assume *q* ∈ *set qs*
show *eval-mpoly ?ell q = eval-mpoly val q*
using *p1 p2 same-eval-list-tailing-zeros*[*of val ?ell q*] ∗ *len*
by *presburger*
qed
then have ∃ *ell*. *length ell* = *biggest-var* ∧ *map* (*rat-of-int* ∘ *Sturm-Tarski.sign* ∘ *eval-mpoly ell*) *qs* = *sign-val*
using *val-prop len*
by (*smt* (*verit*) *comp-apply map-eq-conv*)

}
ultimately have $\exists$ *ell. length ell = biggest-var* $\wedge$ *map* (*rat-of-int* $\circ$ *Sturm-Tarski.sign* $\circ$ *eval-mpoly ell*) *qs = sign-val*
by (*meson linorder-le-less-linear*)
then show *?thesis* **using** *qs-signs* **unfolding** *mpoly-consistent-sign-vectors-def map-mpoly-sign-def*
using *all-lists-def* **by** *auto*
qed

lemma *csv-as-expected*:
assumes *length-nonz*: *length* (*variables-list qs*) > *0*
assumes *n-is*: *n = length* (*variables-list qs*)
assumes *biggest-var-is*: *biggest-var = nth* (*variables-list qs*) (*n−1*) + *1*

assumes *qs-signs*: *qs-signs = mpoly-consistent-sign-vectors qs* (*all-lists biggest-var*)
shows (*sign-val* $\in$ *qs-signs*) $\longleftrightarrow$ ($\exists$ *val.* (*map* (*rat-of-int* $\circ$ *Sturm-Tarski.sign* $\circ$ (*eval-mpoly val*)) *qs = sign-val*))
using *assms csv-as-expected-left*[*of n qs biggest-var qs-signs sign-val*] *csv-as-expected-right*
by *blast*

definition *dim-poly*:: *real mpoly* $\Rightarrow$ *nat*
where *dim-poly q = Max* (*vars q*)

definition *dim-poly-list*:: *real mpoly list* $\Rightarrow$ *nat*
where *dim-poly-list qs = Max* (*variables qs*)

lemma *dim-poly-list-prop*:
assumes *length-nonz*: *variables-list qs* $\neq$ []
assumes *n-is*: *n = length* (*variables-list qs*)
shows *dim-poly-list qs = nth* (*variables-list qs*) (*n−1*)
proof −
let *?biggest-var = nth* (*variables-list qs*) (*n−1*)
have *?biggest-var* $\in$ *set* (*variables-list qs*)
using *assms*
by (*meson diff-less length-greater-0-conv nth-mem zero-less-one*)
then have *h1*: *nth* (*variables-list qs*) (*n−1*) $\in$ *variables qs*
using *variables-prop assms*
using *variables-list-prop* **by** *blast*
have *h2*: $\forall$ *x* $\in$ *variables qs. x* $\leq$ *nth* (*variables-list qs*) (*n−1*)
using *assms biggest-variable-in-sorted-list variables-list-prop variables-prop*
by *presburger*
show *?thesis* **using** *h1 h2 variables-finite* **unfolding** *dim-poly-list-def*
by (*meson Max-eqI*)
qed

lemma *lookup-assump-aux-subset-consistency*:
assumes *val*: $\bigwedge$*p n.* (*p*,*n*) $\in$ *set branch-assms* $\Longrightarrow$ *satisfies-evaluation val p n*
assumes *subset*: *set new-assumps* $\subseteq$ *set branch-assms*
assumes *i-assm*: ($\exists$ *i. lookup-assump-aux* (*Polynomial.lead-coeff r*) *new-assumps*

```
= Some i ∧ i ≠ 0)
  shows (∃ i. lookup-assump-aux (Polynomial.lead-coeff r) branch-assms = Some
i ∧ i ≠ 0)
proof −
 obtain i where i-prop: lookup-assump-aux (Polynomial.lead-coeff r) new-assumps
= Some i
    i ≠ 0
    using i-assm
    by auto
  then have (Polynomial.lead-coeff r, i) ∈ set new-assumps
    by (meson lookup-assump-means-inset)
  then have in-set: (Polynomial.lead-coeff r, i) ∈ set branch-assms
    using subset by auto
  then have satisfies-evaluation val (Polynomial.lead-coeff r) i
    using val by auto
  then have ¬ (satisfies-evaluation val (Polynomial.lead-coeff r) 0)
    using i-prop(2) unfolding satisfies-evaluation-def
   by (metis linorder-neqE-linordered-idom of-int-hom.hom-0-iff one-neq-zero sign-simps(1)
sign-simps(2) sign-simps(3) zero-neq-neg-one)
  then have not-in-set: (Polynomial.lead-coeff r, 0) ∉ set branch-assms
    using val
    by blast
  show ?thesis using in-set not-in-set i-prop(2)
    by (metis inset-means-lookup-assump-some lookup-assump-means-inset)
qed

lemma lookup-assump-aux-subset-consistent-sign:
  assumes val: ⋀p n. (p,n) ∈ set branch-assms ⟹ satisfies-evaluation val p n
  assumes subset: set new-assumps ⊆ set branch-assms
  assumes i1: lookup-assump-aux (Polynomial.lead-coeff r) new-assumps = Some
i1
  assumes i2: lookup-assump-aux (Polynomial.lead-coeff r) branch-assms = Some
i2
  shows Sturm-Tarski.sign i1 = Sturm-Tarski.sign i2
proof −
  have (Polynomial.lead-coeff r, i1) ∈ set new-assumps
    using i1
    by (simp add: lookup-assump-means-inset)
  then have in-set: (Polynomial.lead-coeff r, i1) ∈ set branch-assms
    using subset by auto
  then have sat-eval: satisfies-evaluation val (Polynomial.lead-coeff r) i1
    using val by auto
  have Sturm-Tarski.sign i1 ≠ Sturm-Tarski.sign i2 ⟹ False
  proof −
    assume Sturm-Tarski.sign i1 ≠ Sturm-Tarski.sign i2
    then have ¬ (satisfies-evaluation val (Polynomial.lead-coeff r) i2)
      using sat-eval unfolding satisfies-evaluation-def
      by presburger
    then have not-in-set: (Polynomial.lead-coeff r, i2) ∉ set branch-assms
```

using *val*
by *blast*
then show *False* **using** *i2*
by (*meson lookup-assump-means-inset*)
qed
then show *?thesis*
by *blast*
qed

lemma *lookup-assump-aux-subset-not-none*:
assumes *val*: $\bigwedge p\ n.\ (p,n) \in set\ branch\text{-}assms \Longrightarrow satisfies\text{-}evaluation\ val\ p\ n$
assumes *subset*: *set new-assumps* $\subseteq$ *set branch-assms*
assumes *i1*: *lookup-assump-aux* (*Polynomial.lead-coeff r*) *new-assumps* = *Some i1*
shows $\exists$ *i2*. *lookup-assump-aux* (*Polynomial.lead-coeff r*) *branch-assms* = *Some i2*
proof −
have (*Polynomial.lead-coeff r*, *i1*) $\in$ *set new-assumps*
using *i1*
by (*simp add*: *lookup-assump-means-inset*)
then have *in-set*: (*Polynomial.lead-coeff r*, *i1*) $\in$ *set branch-assms*
using *subset* **by** *auto*
then show *?thesis*
by (*simp add*: *inset-means-lookup-assump-some*)
qed

end

theory *Multiv-Pseudo-Remainder-Sequence*
imports
Multiv-Consistent-Sign-Assignments

begin

12 Functions

definition *mul-pseudo-mod*:: *'a*::{*comm-ring-1*,*semiring-1-no-zero-divisors*} *Polynomial.poly* ⇒ *'a Polynomial.poly* ⇒ *'a Polynomial.poly* **where**
mul-pseudo-mod p q = (
let m =
(*if even*(*Polynomial.degree p*+*1*−*Polynomial.degree q*)
then −*1*
else −*Polynomial.lead-coeff q*) *in*
Polynomial.smult m (*pseudo-mod p q*))

```
function spmods-multiv-aux::
  real mpoly Polynomial.poly ⇒
   real mpoly Polynomial.poly ⇒
   (real mpoly × rat) list ⇒
   ((real mpoly × rat) list × real mpoly Polynomial.poly list) list where
  spmods-multiv-aux p q assumps = (
  if q = 0 then [(assumps, [p])] else
    (case (lookup-assump-aux (Polynomial.lead-coeff q) assumps) of
      None ⇒
        let left = spmods-multiv-aux p (one-less-degree q) ((Polynomial.lead-coeff q,
(0::rat)) # assumps) in
      let res-one = spmods-multiv-aux q (mul-pseudo-mod p q) ((Polynomial.lead-coeff
q, (1::rat)) # assumps) in
      let res-minus-one = spmods-multiv-aux q (mul-pseudo-mod p q) ((Polynomial.lead-coeff
q, (−1::rat)) # assumps) in
        let right-one = map (λx. (fst x, Cons p (snd x))) res-one in
        let right-minus-one = map (λx. (fst x, Cons p (snd x))) res-minus-one in
          append left (append right-one right-minus-one)
      | (Some i) ⇒
        (if i = 0 then  spmods-multiv-aux p (one-less-degree q) assumps
        else
          let res = spmods-multiv-aux q (mul-pseudo-mod p q) assumps in
          map (λx. (fst x, Cons p (snd x))) res
        )
  )) using prod-cases3
   apply blast
  by fastforce
termination
  apply (relation measure (λ(p,q,r). if q = [:0:] then 1 else 2 + Polynomial.degree
q))
       apply blast
      apply (auto)
  using one-less-degree-degree
        apply (metis one-less-degree-def cancel-comm-monoid-add-class.diff-cancel
degree-0-id gr0I monom-0)
  unfolding mul-pseudo-mod-def
  using pseudo-mod(2)
     apply auto[1]
    apply (simp add: degree-pseudo-mod-less)
  apply (metis Multiv-Poly-Props.one-less-degree-def cancel-comm-monoid-add-class.diff-cancel
degree-0-id monom-0 not-gr-zero one-less-degree-degree)
  by (metis degree-pseudo-mod-less degree-smult-eq smult-eq-0-iff)


function spmods-multiv::
  real mpoly Polynomial.poly ⇒
   real mpoly Polynomial.poly ⇒
   (real mpoly × rat) list ⇒
   ((real mpoly × rat) list × (real mpoly Polynomial.poly list)) list
```

where *spmods-multiv p q assumps* = (
if p = *0 then* [(*assumps*,[])] *else*
(*case* (*lookup-assump-aux* (*Polynomial.lead-coeff p*) *assumps*) *of*
None ⇒
let left = *spmods-multiv* (*one-less-degree p*) *q* ((*Polynomial.lead-coeff p*, (*0*::*rat*)) # *assumps*) *in*
let right-one = *spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (*1*::*rat*)) # *assumps*) *in*
let right-minus-one = *spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (−*1*::*rat*)) # *assumps*) *in*
left @ (*right-one* @ *right-minus-one*)
| (*Some i*) ⇒
(*if i* = *0 then spmods-multiv* (*one-less-degree p*) *q assumps*
else
spmods-multiv-aux p q assumps
)
))
using *spmods-multiv-aux.cases* **apply** *blast*
by *force*
termination
apply (*relation measure* (λ(*p*,*q*). *if p* = [:*0*:] *then 1 else 2* + *Polynomial.degree p*))
apply *blast*
apply (*auto*)
using *one-less-degree-degree*
apply (*metis Multiv-Poly-Props.one-less-degree-def cancel-comm-monoid-add-class.diff-cancel degree-0-id monom-0 not-gr-zero*)
by (*metis Multiv-Poly-Props.one-less-degree-def cancel-comm-monoid-add-class.diff-cancel degree-0-id monom-0 not-gr-zero one-less-degree-degree*)

declare *spmods-multiv-aux.simps*[*simp del*]
declare *spmods-multiv.simps*[*simp del*]

13 Proofs

lemma *mul-pseudo-mod-valuation*:
assumes *satisfies-evaluation val* (*Polynomial.lead-coeff p*) *n*
assumes *n* ≠ *0*
assumes *satisfies-evaluation val* (*Polynomial.lead-coeff q*) *m*
assumes *m* ≠ *0*
shows *mul-pseudo-mod* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*) =
eval-mpoly-poly val (*mul-pseudo-mod p q*)
proof −
from *degree-valuation*[*OF assms*(*1*−*2*)] **have**
1: *Polynomial.degree p* = *Polynomial.degree* (*eval-mpoly-poly val p*) **.**
from *degree-valuation*[*OF assms*(*3*−*4*)] **have**
2: *Polynomial.degree q* = *Polynomial.degree* (*eval-mpoly-poly val q*) **.**
from *lead-coeff-valuation*[*OF assms*(*1*−*2*)] **have**
3: *eval-mpoly val* (*Polynomial.lead-coeff p*) = *Polynomial.lead-coeff* (*eval-mpoly-poly*

val p) **.**
from *lead-coeff-valuation*[*OF assms*(*3*−*4*)] **have**
4: *eval-mpoly val* (*Polynomial.lead-coeff q*) = *Polynomial.lead-coeff* (*eval-mpoly-poly val q*) **.**
show *?thesis*
using *assms*
by (*smt* (*verit*, *ccfv-SIG*) *1 2 4 eval-mpoly-map-poly-comm-ring-hom.base.hom-one eval-mpoly-map-poly-comm-ring-hom.base.hom-uminus eval-mpoly-poly-pseudo-mod eval-mpoly-poly-smult mul-pseudo-mod-def of-int-hom.hom-one of-int-hom.hom-uminus*)

qed

lemma *spmods-multiv-aux-induct*[*case-names Base Rec Lookup0 LookupN0*]:
fixes *p q* :: *real mpoly Polynomial.poly*
fixes *assumps* ::(*real mpoly* × *rat*) *list*
assumes *base*: ⋀*p q assumps*. *q* = *0* ⟹ *P p q assumps*
and *rec*: ⋀*p q assumps*.
⟦*q* ≠ *0*;
lookup-assump-aux (*Polynomial.lead-coeff q*) *assumps* = *None*;
P p (*one-less-degree q*) ((*Polynomial.lead-coeff q*, *0*) # *assumps*);
P q (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, *1*) # *assumps*);
P q (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, −*1*) # *assumps*)⟧ ⟹
P p q assumps
and *lookup0*: ⋀*p q assumps*.
⟦*q* ≠ *0*;
lookup-assump-aux (*Polynomial.lead-coeff q*) *assumps* = *Some 0*;
P p (*one-less-degree q*) *assumps*⟧ ⟹ *P p q assumps*
and *lookupN0*: ⋀*p q assumps r*.
⟦*q* ≠ *0*;
lookup-assump-aux (*Polynomial.lead-coeff q*) *assumps* = *Some r*;
r ≠ *0*;
P q (*mul-pseudo-mod p q*) *assumps*⟧ ⟹ *P p q assumps*
shows *P p q assumps*
apply(*induct p q assumps rule*: *spmods-multiv-aux.induct*)
by (*metis base rec lookup0 lookupN0 not-None-eq*)

lemma *spmods-multiv-induct*[*case-names Base Rec Lookup0 LookupN0*]:
fixes *p q* :: *real mpoly Polynomial.poly*
fixes *assumps* ::(*real mpoly* × *rat*) *list*
assumes *base*: ⋀*p q assumps*. *p* = *0* ⟹ *P p q assumps*
and *rec*: ⋀*p q assumps*.
⟦*p* ≠ *0*;
lookup-assump-aux (*Polynomial.lead-coeff p*) *assumps* = *None*;
P (*one-less-degree p*) *q* ((*Polynomial.lead-coeff p*, *0*) # *assumps*)⟧ ⟹
P p q assumps
and *lookup0*: ⋀*p q assumps*.
⟦*p* ≠ *0*;
lookup-assump-aux (*Polynomial.lead-coeff p*) *assumps* = *Some 0*;

```
    P (one-less-degree p) q assumps⟧ ⟹ P p q assumps
  and lookupN0: ⋀p q assumps r.
    ⟦p ≠ 0;
    lookup-assump-aux (Polynomial.lead-coeff p) assumps = Some r;
    r ≠ 0⟧ ⟹ P p q assumps
 shows P p q assumps
 apply(induct p q assumps rule: spmods-multiv.induct)
 by (metis base rec lookup0 lookupN0 not-None-eq)


lemma spmods-multiv-aux-assum-acc:
 assumes (acc',seq') ∈ set (spmods-multiv-aux p q acc)
 shows set acc ⊆ set acc'
 using assms
proof (induct p q acc arbitrary:acc' seq' rule: spmods-multiv-aux-induct)
 case (Base p q assumps)
 then show ?case by (auto simp add: spmods-multiv-aux.simps)
next
 case (Rec p q assumps)
 then show ?case using spmods-multiv-aux.simps[of p q assumps]
  by (smt (z3) Un-iff imageE insert-subset list.set(2) list.set-map old.prod.inject
option.simps(4) prod.collapse set-append)

next
 case (Lookup0 p q assumps)
 then show ?case
  by (auto simp add: spmods-multiv-aux.simps[of p q assumps])
next
 case (LookupN0 p q assumps r)
 then show ?case using spmods-multiv-aux.simps[of p q assumps]
  using option.simps(5) prod.collapse by fastforce
qed

lemma spmods-multiv-assum-acc:
 assumes (acc',seq') ∈ set (spmods-multiv p q acc)
 shows set acc ⊆ set acc'
 using assms
proof (induct p q acc arbitrary:acc' seq' rule: spmods-multiv-induct)
 case (Base p q assumps)
 then show ?case by (auto simp add: spmods-multiv.simps)
next
 case (Rec p q assumps)
 then show ?case
  using spmods-multiv-aux-assum-acc spmods-multiv.simps[of p q assumps]
  by (metis Un-iff insert-subset list.set(2) option.simps(4) set-append)
next
 case (Lookup0 p q assumps)
 then show ?case
  by (auto simp add: spmods-multiv.simps[of p q assumps])
```

next
case (*LookupN0 p q assumps r*)
then show *?case*
using *spmods-multiv-aux-assum-acc*
by (*auto simp add*: *spmods-multiv.simps*[*of p q assumps*])
qed

lemma *lookup-assum-aux-mem*:
assumes *lookup-assump-aux x ls* = *Some i*
shows (*x*,*i*) ∈ *set ls*
using *assms*
apply (*induction ls*)
apply *force*
by (*metis fst-conv list.set-intros*(*1*) *list.set-intros*(*2*) *lookup-assump-aux.simps*(*2*) *old.prod.exhaust option.inject prod.sel*(*2*))

lemma *matches-ss*:
assumes (*Polynomial.lead-coeff p*,*m*) ∈ *set assumps m* ≠ *0*
assumes (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q acc*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
shows *map* (*eval-mpoly-poly val*) *sturm-seq* =
spmods (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*)
using *assms*
proof (*induct p q acc arbitrary*:*assumps sturm-seq m rule*: *spmods-multiv-aux-induct*)
case (*Base p q assumps*)
then show *?case*
using *lead-coeff-valuation satisfies-evaluation-nonzero spmods-multiv-aux.simps*
by *fastforce*
next
case *ih*: (*Rec p q acc*)
let *?left* = *spmods-multiv-aux p* (*one-less-degree q*) ((*Polynomial.lead-coeff q*, (*0*::*rat*)) # *acc*)
let *?res-one* = *spmods-multiv-aux q* (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, (*1*::*rat*)) # *acc*)
let *?res-minus-one* = *spmods-multiv-aux q* (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, (−*1*::*rat*)) # *acc*)
have *rec*: (*assumps*, *sturm-seq*) ∈ *set ?left* ∨
(*assumps*, *sturm-seq*) ∈ *set* (*map* (λ*x*. (*fst x*, *Cons p* (*snd x*))) *?res-one*) ∨
(*assumps*, *sturm-seq*) ∈ *set* (*map* (λ*x*. (*fst x*, *Cons p* (*snd x*))) *?res-minus-one*)
using *ih* **by** (*auto simp add*: *spmods-multiv-aux.simps*[*of p q acc*])
moreover {
assume (*assumps*, *sturm-seq*) ∈ *set ?left*
then have *map* (*eval-mpoly-poly val*) *sturm-seq* = *spmods* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*)
by (*metis eval-mpoly-poly-one-less-degree ih.hyps*(*3*) *ih.prems*(*1*) *ih.prems*(*2*) *ih.prems*(*4*) *insert-subset list.set*(*2*) *spmods-multiv-aux-assum-acc*)
}
moreover {

assume $**$:
(*assumps*, *sturm-seq*) ∈ *set* (*map* (λ*x*. (*fst x*, *Cons p* (*snd x*))) *?res-one*) ∨
(*assumps*, *sturm-seq*) ∈ *set* (*map* (λ*x*. (*fst x*, *Cons p* (*snd x*))) *?res-minus-one*)
then obtain *s ss* **where** *ss*:*sturm-seq* = *s*#*ss*
and *rec*:(*assumps*,*ss*) ∈ *set ?res-one* ∨ (*assumps*,*ss*) ∈ *set ?res-minus-one*
by *auto*
have *lead-coeff-inset*: (*Polynomial.lead-coeff q*,*1*) ∈ *set assumps* ∨ (*Polynomial.lead-coeff q*,−*1*) ∈ *set assumps*
using $**$ *spmods-multiv-aux-assum-acc* **by** *fastforce*
then have *A*:*map* (*eval-mpoly-poly val*) *ss* =
spmods (*eval-mpoly-poly val q*) (*eval-mpoly-poly val* (*mul-pseudo-mod p q*))
by (*metis ih.hyps*(*4*) *ih.hyps*(*5*) *ih.prems*(*4*) *local.rec zero-neq-neg-one zero-neq-one*)
have *B*:*spmods* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*) =
((*eval-mpoly-poly val p*) # (*spmods* (*eval-mpoly-poly val q*) (*mul-pseudo-mod* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*))))
by (*metis ih.prems*(*1*) *ih.prems*(*2*) *ih.prems*(*4*) *lead-coeff-valuation leading-coeff-0-iff mul-pseudo-mod-def satisfies-evaluation-nonzero spmods.simps*)
have *C*: *mul-pseudo-mod* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*) = *eval-mpoly-poly val* (*mul-pseudo-mod p q*)
by (*metis lead-coeff-inset ih.prems*(*1*) *ih.prems*(*2*) *ih.prems*(*4*) *mul-pseudo-mod-valuation zero-neq-neg-one zero-neq-one*)
have *map* (*eval-mpoly-poly val*) *sturm-seq* = *spmods* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*)
using *A B C rec ss* $**$ **by** *auto*
}
ultimately show *?case*
using *local.rec* **by** *blast*
next
case (*Lookup0 p q acc*)
then have *rec*: (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p* (*one-less-degree q*) *acc*)
by (*auto simp add*: *spmods-multiv-aux.simps*[*of p q acc*])
have (*Polynomial.lead-coeff q*,*0*) ∈ *set acc*
by (*simp add*: *Lookup0.hyps*(*2*) *lookup-assum-aux-mem*)
then have *satisfies-evaluation val* (*Polynomial.lead-coeff q*) *0*
using *Lookup0.prems*(*3*) *Lookup0.prems*(*4*) *spmods-multiv-aux-assum-acc* **by** *blast*
then have *eval-mpoly-poly val* (*one-less-degree q*) = (*eval-mpoly-poly val q*)
by (*auto simp add*: *eval-mpoly-poly-one-less-degree*)
then show *?case*
using *Lookup0.hyps*(*3*) *Lookup0.prems*(*1*) *Lookup0.prems*(*2*) *Lookup0.prems*(*4*) *local.rec* **by** *presburger*
next
case *ih*:(*LookupN0 p q acc r*)
then have *asm*:(*assumps*, *sturm-seq*) ∈ *set* (
map (λ*x*. (*fst x*, *Cons p* (*snd x*)))
(*spmods-multiv-aux q* (*mul-pseudo-mod p q*) *acc*))
by (*auto simp add*: *spmods-multiv-aux.simps*[*of p q acc*])
then obtain *s ss* **where** *ss*:*sturm-seq* = *s*#*ss*

and *rec*:(*assumps*,*ss*) ∈ *set* (*spmods-multiv-aux q* (*mul-pseudo-mod p q*) *acc*)
by *auto*
have *A*:*map* (*eval-mpoly-poly val*) *ss* = *spmods* (*eval-mpoly-poly val q*) (*eval-mpoly-poly val* (*mul-pseudo-mod p q*))
using *ih*(*4*)[*OF - - rec*]
by (*meson ih.hyps*(*2*) *ih.hyps*(*3*) *ih.prems*(*4*) *in-mono local.rec lookup-assump-means-inset spmods-multiv-aux-assum-acc*)
have *B*:*spmods* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*) =
((*eval-mpoly-poly val p*) # (*spmods* (*eval-mpoly-poly val q*) (*mul-pseudo-mod* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*))))
by (*metis ih*(*5*) *ih*(*6*) *ih.prems*(*4*) *lead-coeff-valuation leading-coeff-0-iff mul-pseudo-mod-def satisfies-evaluation-nonzero spmods.simps*)
have *C*: *mul-pseudo-mod* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*) = *eval-mpoly-poly val* (*mul-pseudo-mod p q*)
by (*meson ih.hyps*(*2*) *ih.hyps*(*3*) *ih.prems*(*1*) *ih.prems*(*2*) *ih.prems*(*4*) *local.rec lookup-assum-aux-mem mul-pseudo-mod-valuation spmods-multiv-aux-assum-acc subsetD*)
show *?case*
using *A B C rec ss asm* **by** *force*
qed

lemma *spmods-multiv-aux-sturm-lc*:
assumes (*Polynomial.lead-coeff p*,*m*) ∈ *set acc m* ≠ *0*
assumes (*acc'*,*seq'*) ∈ *set* (*spmods-multiv-aux p q acc*)
assumes *el* ∈ *set seq'*
shows ∃ *r*. (*Polynomial.lead-coeff el*,*r*) ∈ *set acc'* ∧ *r* ≠ *0*
using *assms*
proof (*induct p q acc arbitrary*:*acc' seq' el m rule*: *spmods-multiv-aux-induct*)
case (*Base p q acc*)
then show *?case*
using *empty-iff fst-conv list.set*(*1*) *prod.sel*(*2*) *set-ConsD spmods-multiv-aux.simps*
by *auto*
next
case (*Rec p q acc*)
then show *?case*
apply (*auto simp add*: *spmods-multiv-aux.simps*[*of p q acc*])
apply (*meson Rec.prems*(*3*) *spmods-multiv-aux-assum-acc subset-eq*)
apply (*metis zero-neq-one*)
apply (*meson Rec.prems*(*3*) *spmods-multiv-aux-assum-acc subset-iff*)
by (*metis zero-neq-neg-one*)

next
case (*Lookup0 p q acc*)
then show *?case*
by (*auto simp add*: *spmods-multiv-aux.simps*[*of p q acc*])
next
case (*LookupN0 p q acc r*)
then show *?case*
apply (*auto simp add*: *spmods-multiv-aux.simps*[*of p q acc*])

using *spmods-multiv-aux-assum-acc* **apply** *blast*
by (*meson lookup-assum-aux-mem*)
qed

lemma *spmods-multiv-sturm-lc*:
assumes (*acc'*,*seq'*) ∈ *set* (*spmods-multiv p q acc*)
assumes *el* ∈ *set seq'*
shows ∃ *r*. (*Polynomial.lead-coeff el*,*r*) ∈ *set acc'* ∧ *r* ≠ *0*
using *assms*
proof (*induct p q acc arbitrary*:*acc' seq' rule*: *spmods-multiv-induct*)
case (*Base p q assumps*)
then show *?case*
using *spmods-multiv.simps*
by *simp*
next
case (*Rec p q assumps*)
then show *?case*
apply (*auto simp add*: *spmods-multiv.simps*[*of p q assumps*])
using *spmods-multiv-aux-sturm-lc*
apply (*metis list.set-intros*(*1*) *zero-neq-one*)
by (*metis list.set-intros*(*1*) *spmods-multiv-aux-sturm-lc zero-neq-neg-one*)
next
case (*Lookup0 p q assumps*)
then show *?case*
by (*auto simp add*: *spmods-multiv.simps*[*of p q assumps*])
next
case (*LookupN0 p q assumps r*)
then show *?case* **using** *spmods-multiv.simps*[*of p q assumps*]
spmods-multiv-aux-sturm-lc lookup-assum-aux-mem
by (*smt* (*verit*, *ccfv-threshold*) *option.simps*(*5*))

qed

lemma *matches-len-complete*:
assumes ⋀*p n*. (*p*,*n*) ∈ *set acc* ⟹ *satisfies-evaluation val p n*
obtains *assumps sturm-seq* **where**
(*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q acc*)
⋀ *p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
using *assms*
proof (*induct p q acc arbitrary*: *thesis rule*: *spmods-multiv-aux-induct*)
case (*Base p q acc*)
then show *?case*
by (*simp add*: *spmods-multiv-aux.simps*)
next
case *ih*: (*Rec p q acc*)
let *?left* = *spmods-multiv-aux p* (*one-less-degree q*) ((*Polynomial.lead-coeff q*,
(*0*::*rat*)) # *acc*)
let *?res-one* = *spmods-multiv-aux q* (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff*

```
q, (1::rat)) # acc)
 let ?res-minus-one = spmods-multiv-aux q (mul-pseudo-mod p q) ((Polynomial.lead-coeff
q, (−1::rat)) # acc)
  have satisfies-evaluation val (Polynomial.lead-coeff q) 0 ∨
    satisfies-evaluation val (Polynomial.lead-coeff q) 1 ∨
    satisfies-evaluation val (Polynomial.lead-coeff q) (−1)
    unfolding satisfies-evaluation-def
    apply auto
    using Sturm-Tarski.sign-cases
    by (metis of-int-hom.hom-one of-int-minus)
  then have q:
  (∀ p n. (p,n) ∈ set ((Polynomial.lead-coeff q, 0) # acc) ⟶ satisfies-evaluation
val p n) ∨
  (∀ p n. (p,n) ∈ set ((Polynomial.lead-coeff q, 1) # acc) ⟶ satisfies-evaluation
val p n) ∨
  (∀ p n. (p,n) ∈ set ((Polynomial.lead-coeff q, −1) # acc) ⟶ satisfies-evaluation
val p n)
    by (simp add: ih.prems(2))
  moreover {
    assume ∗:(∀ p n. (p,n) ∈ set ((Polynomial.lead-coeff q, 0) # acc) ⟶ satis-
fies-evaluation val p n)
    then have ?case using ∗ ih(3)
      by (metis (no-types, lifting) Un-iff ih.hyps(1) ih.hyps(2) ih.prems(1) op-
tion.case(1) set-append spmods-multiv-aux.simps)
  }
  moreover {
    assume ∗:(∀ p n. (p,n) ∈ set ((Polynomial.lead-coeff q, 1) # acc) ⟶ satis-
fies-evaluation val p n)
    then have ?case using ∗ ih(4)
    by (smt (z3) Un-iff fst-conv ih.hyps(1) ih.hyps(2) ih.prems(1) in-set-conv-decomp
list.simps(9) map-append option.case(1) set-append spmods-multiv-aux.simps)
  }
  moreover {
    assume ∗:(∀ p n. (p,n) ∈ set ((Polynomial.lead-coeff q, −1) # acc) ⟶ satis-
fies-evaluation val p n)
    then have ?case using ∗ ih(5)
    by (smt (z3) Un-iff fst-conv ih.hyps(1) ih.hyps(2) ih.prems(1) in-set-conv-decomp
list.simps(9) map-append option.case(1) set-append spmods-multiv-aux.simps)
  }
  ultimately show ?case
    by fastforce
next
  case (Lookup0 p q acc)
  then show ?case
    by (auto simp add: spmods-multiv-aux.simps[of p q acc])
next
  case ih: (LookupN0 p q assumps r)
  then obtain assumps′ sturm-seq′ where
    (assumps′, sturm-seq′) ∈ set (spmods-multiv-aux q (mul-pseudo-mod p q) as-
```

sumps)
(⋀*p n*. (*p*, *n*) ∈ *set assumps'* ⟹ *satisfies-evaluation val p n*)
by *blast*
then show *?case* **using** *ih spmods-multiv-aux.simps*[*of p q assumps*] *fst-conv image-eqI*
by (*smt* (*verit*) *list.set-map option.simps*(*5*))

qed

lemma *spmods-multiv-nonz-some*:
fixes *p*:: *real mpoly Polynomial.poly*
fixes *q*:: *real mpoly Polynomial.poly*
assumes *inset*: (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv p q acc*)
shows *p* ≠ *0* ⟹ ∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff p*) *assumps* = *Some i*
using *assms*
proof (*induct p q acc rule*: *spmods-multiv-induct*)
case (*Base p q acc*)
then show *?case* **by** *auto*
next
case (*Rec p q acc*)
then have (*lookup-assump-aux* (*Polynomial.lead-coeff p*) *acc*) = *None*
by *meson*
then have *set* (*spmods-multiv p q acc*) =
set (*spmods-multiv* (*one-less-degree p*) *q* ((*Polynomial.lead-coeff p*, (*0*::*rat*)) # *acc*))
∪ *set* (*spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (*1*::*rat*)) # *acc*))
∪ *set* (*spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (−*1*::*rat*)) # *acc*))
by (*simp add*: *Rec.prems*(*1*) *spmods-multiv.simps sup-assoc*)
then have (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv* (*one-less-degree p*) *q* ((*Polynomial.lead-coeff p*, (*0*::*rat*)) # *acc*))
∨ (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (*1*::*rat*)) # *acc*))
∨ (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (−*1*::*rat*)) # *acc*))
using *Rec.prems*(*2*) **by** *blast*
then show *?case*
using *spmods-multiv-assum-acc spmods-multiv-aux-assum-acc*
by (*metis insert-subset inset-means-lookup-assump-some list.set*(*2*))
next
case (*Lookup0 p q acc*)
then show *?case*
by (*meson inset-means-lookup-assump-some lookup-assum-aux-mem spmods-multiv-assum-acc subset-eq*)
next
case (*LookupN0 p q acc r*)
then show *?case*
by (*meson inset-means-lookup-assump-some lookup-assump-means-inset spmods-multiv-assum-acc subsetD*)

qed

lemma *spmods-multiv-aux-nonz-some*:
fixes *p*:: *real mpoly Polynomial.poly*
fixes *q*:: *real mpoly Polynomial.poly*
assumes *inset*: (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q acc*)
shows *q* ≠ *0* ⟹ ∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff q*) *assumps* = *Some i*
using *assms*
proof (*induct p q acc rule*: *spmods-multiv-aux-induct*)
case (*Base p q acc*)
then show *?case* **by** *auto*
next
case (*Rec p q acc*)
then have (*lookup-assump-aux* (*Polynomial.lead-coeff q*) *acc*) = *None*
by *meson*
then have *set* (*spmods-multiv-aux p q acc*) =
set (*spmods-multiv-aux p* (*one-less-degree q*) ((*Polynomial.lead-coeff q*, (*0*::*rat*)) # *acc*))
∪ *set* (*map* (λ*x*. (*fst x*, *Cons p* (*snd x*))) (*spmods-multiv-aux q* (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, (*1*::*rat*)) # *acc*)))
∪ *set* (*map* (λ*x*. (*fst x*, *Cons p* (*snd x*))) (*spmods-multiv-aux q* (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, (−*1*::*rat*)) # *acc*)))
using *Rec.prems*(*1*) *spmods-multiv-aux.simps*
by (*simp add*: *Rec.prems*(*1*) *spmods-multiv-aux.simps sup-assoc*)
then have *bigh*: (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p* (*one-less-degree q*) ((*Polynomial.lead-coeff q*, (*0*::*rat*)) # *acc*))
∨ (*assumps*, *sturm-seq*) ∈ *set* (*map* (λ*x*. (*fst x*, *Cons p* (*snd x*))) (*spmods-multiv-aux q* (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, (*1*::*rat*)) # *acc*)))
∨ (*assumps*, *sturm-seq*) ∈ *set* (*map* (λ*x*. (*fst x*, *Cons p* (*snd x*))) (*spmods-multiv-aux q* (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, (−*1*::*rat*)) # *acc*)))
using *Rec.prems*(*2*)
by *blast*
have *h1*: (⋀*acc' seq' p q acc*. (*acc'*, *seq'*) ∈ *set* (*spmods-multiv-aux p q acc*) ⟹ *set acc* ⊆ *set acc'*) ⟹
(*assumps*, *sturm-seq*)
∈ *set* (*spmods-multiv-aux p* (*Multiv-Poly-Props.one-less-degree q*)
((*Polynomial.lead-coeff q*, *0*) # *acc*)) ⟹
∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff q*) *assumps* = *Some i*
by (*meson inset-means-lookup-assump-some list.set-intros*(*1*) *subsetD*)
have *h2*: ⋀*b*. (⋀*acc' seq' p q acc*. (*acc'*, *seq'*) ∈ *set* (*spmods-multiv-aux p q acc*) ⟹ *set acc* ⊆ *set acc'*) ⟹
(*assumps*, *b*)
∈ *set* (*spmods-multiv-aux q* (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, *1*) # *acc*)) ⟹
sturm-seq = *p* # *b* ⟹ ∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff q*) *assumps* = *Some i*
by (*meson inset-means-lookup-assump-some list.set-intros*(*1*) *subsetD*)
have *h3*: ⋀*b*. (⋀*acc' seq' p q acc*. (*acc'*, *seq'*) ∈ *set* (*spmods-multiv-aux p q acc*)

$\Longrightarrow$ *set acc* $\subseteq$ *set acc'*) $\Longrightarrow$
(*assumps*, *b*)
$\in$ *set* (*spmods-multiv-aux q* (*mul-pseudo-mod p q*) ((*Polynomial.lead-coeff q*, $-$ *1*) # *acc*)) $\Longrightarrow$
sturm-seq = *p* # *b* $\Longrightarrow$ $\exists$ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff q*) *assumps* = *Some i*
by (*meson inset-means-lookup-assump-some list.set-intros*(*1*) *subsetD*)
show *?case*
using *bigh spmods-multiv-aux-assum-acc h1 h2 h3*
by *auto*
next
case (*Lookup0 p q acc*)
then show *?case*
by (*meson inset-means-lookup-assump-some lookup-assum-aux-mem spmods-multiv-aux-assum-acc subsetD*)
next
case (*LookupN0 p q acc r*)
then show *?case*
by (*meson inset-means-lookup-assump-some lookup-assump-means-inset spmods-multiv-aux-assum-acc subsetD*)
qed

lemma *spmods-multiv-sound*:
assumes (*assumps*, *sturm-seq*) $\in$ *set* (*spmods-multiv p q acc*)
assumes $\bigwedge$*p n*. (*p*,*n*) $\in$ *set assumps* $\Longrightarrow$ *satisfies-evaluation val p n*
shows *map* (*eval-mpoly-poly val*) *sturm-seq* =
spmods (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*)
using *assms*
proof (*induct p q acc arbitrary*:*assumps sturm-seq rule*: *spmods-multiv-induct*)
case (*Base p q assumps*)
then show *?case*
by (*simp add*: *spmods-multiv.simps*)
next
case (*Rec p q assumps*)
then show *?case*
by (*smt* (*verit*, *best*) *UnE eval-mpoly-poly-one-less-degree list.set-intros*(*1*) *matches-ss option.simps*(*4*) *set-append spmods-multiv.simps spmods-multiv-assum-acc spmods-multiv-aux-assum-acc subsetD zero-neq-neg-one zero-neq-one*)
next
case (*Lookup0 p q assumps*)
define *pval* **where** *pval*:*pval* = *eval-mpoly-poly val p*
define *qval* **where** *qval*:*qval* = *eval-mpoly-poly val q*
have (*Polynomial.lead-coeff p*,*0*) $\in$ *set assumps*
using *Lookup0.hyps Lookup0.prems*
by (*meson lookup-assum-aux-mem spmods-multiv-assum-acc subset-code*(*1*))
then have *satisfies-evaluation val* (*Polynomial.lead-coeff p*) *0*
using *Lookup0.hyps Lookup0.prems* **by** *blast*
from *eval-mpoly-poly-one-less-degree*[*OF this*] **have**
eval-prop: *eval-mpoly-poly val* (*one-less-degree p*) = *pval* **using** *pval qval*

```
    by auto
  have map (eval-mpoly-poly val) sturm-seq = spmods pval qval
    using Lookup0.hyps Lookup0.prems pval qval
    by (simp add: eval-prop spmods-multiv.simps)
  then show ?case
    using pval qval by blast
next
  case (LookupN0 p q assumps r)
  define pval where pval:pval = eval-mpoly-poly val p
  define qval where qval:qval = eval-mpoly-poly val q
  {
     assume right: ∃ k. lookup-assump-aux (Polynomial.lead-coeff p) assumps =
Some k ∧k ≠ 0
     then obtain k where k-prop: lookup-assump-aux (Polynomial.lead-coeff p)
assumps = Some k ∧k ≠ 0
      by auto
    then have (Polynomial.lead-coeff p,k) ∈ set assumps
      using spmods-multiv-aux-assum-acc
      by (simp add: lookup-assum-aux-mem)
    have k ≠ 0
      using k-prop by auto
    then have
      map (eval-mpoly-poly val) sturm-seq = spmods pval qval
      using matches-ss[of p k assumps sturm-seq q - val] right LookupN0.prems(2)
LookupN0.prems LookupN0.hyps
      using ‹(Polynomial.lead-coeff p, k) ∈ set assumps› pval qval
      by (simp add: spmods-multiv.simps)
  }
  then have map (eval-mpoly-poly val) sturm-seq = spmods pval qval
    using LookupN0.hyps LookupN0.prems
      lookup-assump-aux-subset-consistency option.case(2) spmods-multiv.simps sp-
mods-multiv-aux-assum-acc
   by (smt (verit) Sturm-Tarski.sign-def in-mono lookup-assum-aux-mem of-int-hom.injectivity
satisfies-evaluation-def sign-simps(2) spmods-multiv-nonz-some)
  then show ?case
    using pval qval by blast
qed

end


theory Hybrid-Multiv-Matrix
  imports

    Factor-Algebraic-Polynomial.Poly-Connection
    Multiv-Pseudo-Remainder-Sequence
    BenOr-Kozen-Reif.More-Matrix
    HOL−Library.Mapping
    BenOr-Kozen-Reif.Renegar-Algorithm
```

begin

14 Find CSAS to qs at zeros of p

14.1 Towards Tarski Queries

fun *sminus*:: *nat list* ⇒ *rat list* ⇒ *int* **where**
sminus degree-list sturm-seq = *changes* (*map* (λ*i*. (−*1*)^(*nth degree-list i*)∗(*nth sturm-seq i*)) [*0*..< *length degree-list*])

definition *changes-R-smods-multiv*:: *rat list* ⇒ *nat list* ⇒ *int*
where *changes-R-smods-multiv signs-list degree-list* ≡ (*sminus degree-list signs-list*) − (*changes signs-list*)

definition *changes-R-smods-multiv-val*:: *real mpoly Polynomial.poly list* ⇒ *real list* ⇒ *int* **where**
changes-R-smods-multiv-val sturm-seq val ≡ (*let* (*eval-ss*::*real Polynomial.poly list*) = (*eval-mpoly-poly-list val sturm-seq*) *in* (*changes-poly-neg-inf eval-ss* − *changes-poly-pos-inf eval-ss*))

14.2 Building the Matrix Equation

type-synonym *rmpoly* = *real mpoly Polynomial.poly*
type-synonym *assumps* = (*real mpoly* × *rat*) *list*
type-synonym *matrix-equation* = (*rat mat* × ((*nat list* ∗ *nat list*) *list* × *rat list list*))

definition *base-case-info-M*:: (*assumps* × *matrix-equation*) *list*
where *base-case-info-M* = [([], *base-case-info-R*)]

definition *base-case-info-M-assumps*:: *assumps* ⇒ (*assumps* × *matrix-equation*) *list*
where *base-case-info-M-assumps init-assumps* = [(*init-assumps*, *base-case-info-R*)]

fun *combine-systems-single-M*:: *rmpoly* ⇒ *rmpoly list* ⇒ (*assumps* × *matrix-equation*) ⇒ *rmpoly list* ⇒ (*assumps* × *matrix-equation*) ⇒ (*assumps* × *matrix-equation*)
where *combine-systems-single-M p q1* (*a1*, *m1*) *q2* (*a2*,*m2*) =
(*append a1 a2*, *snd* (*combine-systems-R p* (*q1*, *m1*) (*q2*, *m2*)))

fun *combine-systems-M*:: *rmpoly* ⇒ *rmpoly list* ⇒ (*assumps* × *matrix-equation*) *list* ⇒ *rmpoly list* ⇒
(*assumps* × *matrix-equation*) *list* => *rmpoly list* × ((*assumps* × *matrix-equation*) *list*)
where *combine-systems-M p q1 list1 q2 list2* =
(*append q1 q2*, *concat* (*map* (λ*l1*. (*map* (λ*l2*. *combine-systems-single-M p q1 l1 q2 l2*) *list2*)) *list1*))

definition *construct-NofI-R-spmods*:: *rmpoly* ⇒ *assumps* ⇒ *rmpoly list* ⇒ *rmpoly list* ⇒ (*assumps* × (*rmpoly list*)) *list*
where *construct-NofI-R-spmods p assumps I1 I2* = (
let new-p = *sum-list* (*map* (λ*x*. *x*^2) (*p* # *I1*)) *in*
spmods-multiv new-p ((*pderiv new-p*)∗(*prod-list I2*))) *assumps*

fun *construct-NofI-single-M*:: (*assumps* × (*rmpoly list*)) ⇒
(*assumps* × *rat*)
where *construct-NofI-single-M* (*input-assumps*, *ss*) =
(*let lcs* = *lead-coeffs ss*;
sa-list = *map* (λ*lc*. *lookup-assump lc input-assumps*) *lcs*;
degrees-list = *degrees ss in*
(*input-assumps*, *rat-of-int* (*changes-R-smods-multiv sa-list degrees-list*)))

fun *construct-NofI-M*:: *rmpoly* ⇒ *assumps* ⇒ *rmpoly list* ⇒ *rmpoly list* => (*assumps* × *rat*) *list*
where *construct-NofI-M p assumps I1 I2* =
(*let ss-list* = *construct-NofI-R-spmods p assumps I1 I2 in*
map construct-NofI-single-M ss-list)

fun *pull-out-pairs*:: *rmpoly list* ⇒ (*nat list* ∗ *nat list*) *list* ⇒ (*rmpoly list* × *rmpoly list*) *list*
where *pull-out-pairs qs Is* =
map (λ(*I1*, *I2*). ((*retrieve-polys qs I1*), (*retrieve-polys qs I2*))) *Is*

fun *construct-rhs-vector-rec-M*:: *rmpoly* ⇒ *assumps* ⇒ (*rmpoly list* × *rmpoly list*) *list* ⇒ (*assumps* × *rat list*) *list*
where *construct-rhs-vector-rec-M p assumps* [] = [(*assumps*, [])]
| *construct-rhs-vector-rec-M p assumps* ((*qs1*, *qs2*)#[]) =
(*let TQ-list* = *construct-NofI-M p assumps qs1 qs2 in*
map (λ(*new-assumps*, *tq*). (*new-assumps*, [*tq*])) *TQ-list*)
| *construct-rhs-vector-rec-M p assumps* ((*qs1*, *qs2*)#*T*) =
concat (*let TQ-list* = *construct-NofI-M p assumps qs1 qs2 in*
(*map* (λ(*new-assumps*, *tq*). (*let rec* = *construct-rhs-vector-rec-M p new-assumps T in*
map (λ*r*. (*fst r*, *tq*#*snd r*)) *rec*)) *TQ-list*))

definition *construct-rhs-vector-M*:: *rmpoly* ⇒ *assumps* ⇒ *rmpoly list* ⇒ (*nat list* ∗ *nat list*) *list* ⇒ (*assumps* × *rat vec*) *list*
where *construct-rhs-vector-M p assumps qs Is* =
map (λ*res*. (*fst res*, *vec-of-list* (*snd res*))) (*construct-rhs-vector-rec-M p assumps* (*pull-out-pairs qs Is*))

definition *solve-for-lhs-single-M*:: *rmpoly* ⇒ *rmpoly list* ⇒ (*nat list* ∗ *nat list*) *list* ⇒ *rat mat* ⇒ *rat vec* ⇒ *rat vec*
where *solve-for-lhs-single-M p qs subsets matr rhs-vector* =
mult-mat-vec (*matr-option* (*dim-row matr*) (*mat-inverse-var matr*)) *rhs-vector*

definition *solve-for-lhs-M*:: *rmpoly* ⇒ *assumps* ⇒ *rmpoly list* ⇒ (*nat list* ∗ *nat*

list) *list* ⇒ *rat mat* ⇒ (*assumps* × *rat vec*) *list*
where *solve-for-lhs-M p assumps qs subsets matr* =
map (λ*rhs*. (*fst rhs*, *solve-for-lhs-single-M p qs subsets matr* (*snd rhs*))) (*construct-rhs-vector-M p assumps qs subsets*)

14.3 Reduction

fun *reduce-system-single-M*:: *rmpoly* ⇒ *rmpoly list* ⇒ (*assumps* × *matrix-equation*) ⇒ (*assumps* × *matrix-equation*) *list*
where *reduce-system-single-M p qs* (*assumps*, (*m*,*subs*,*signs*)) =
map (λ*lhs*. (*fst lhs*, *reduction-step-R m signs subs* (*snd lhs*))) (*solve-for-lhs-M p assumps qs subs m*)

fun *reduce-system-M*:: *rmpoly* ⇒ *rmpoly list* ⇒ (*assumps* × *matrix-equation*) *list* ⇒ (*assumps* × *matrix-equation*) *list*
where *reduce-system-M p qs input-list* = *concat* (*map* (*reduce-system-single-M p qs*) *input-list*)

14.4 Top-level Function

fun *calculate-data-M*:: *rmpoly* ⇒ *rmpoly list* ⇒ (*assumps* × *matrix-equation*) *list*
where
calculate-data-M p qs =
(*let len* = *length qs in*
if len = *0 then map* (λ(*assumps*,(*a*,(*b*,*c*))). (*assumps*, (*a*,*b*,*map* (*drop 1*) *c*))) (*reduce-system-M p* [*1*] *base-case-info-M*)
else if len ≤ *1 then reduce-system-M p qs base-case-info-M*
else
(*let q1* = *take* (*len div 2*) *qs*; *left* = *calculate-data-M p q1*;
q2 = *drop* (*len div 2*) *qs*; *right* = *calculate-data-M p q2*;
comb = *combine-systems-M p q1 left q2 right in*
reduce-system-M p (*fst comb*) (*snd comb*)
)
)

fun *calculate-data-assumps-M*:: *rmpoly* ⇒ *rmpoly list* ⇒ *assumps* ⇒ (*assumps* × *matrix-equation*) *list*
where
calculate-data-assumps-M p qs init-assumps =
(*let len* = *length qs in*
if len = *0 then map* (λ(*assumps*,(*a*,(*b*,*c*))). (*assumps*, (*a*,*b*,*map* (*drop 1*) *c*))) (*reduce-system-M p* [*1*] (*base-case-info-M-assumps init-assumps*))
else if len ≤ *1 then reduce-system-M p qs* (*base-case-info-M-assumps init-assumps*)
else
(*let q1* = *take* (*len div 2*) *qs*; *left* = *calculate-data-assumps-M p q1 init-assumps*;
q2 = *drop* (*len div 2*) *qs*; *right* = *calculate-data-assumps-M p q2 init-assumps*;
comb = *combine-systems-M p q1 left q2 right in*
reduce-system-M p (*fst comb*) (*snd comb*)

)
)

end

theory *Hybrid-Multiv-Algorithm*

imports *Hybrid-Multiv-Matrix*
Virtual-Substitution.ExportProofs

begin

15 Most recent code

function *lc-assump-generation*:: *rmpoly* ⇒ *assumps*⇒ (*assumps* × *rmpoly*) *list*
where *lc-assump-generation q assumps* =
(*if q* = *0 then* [(*assumps*, *0*)] *else*
(*case* (*lookup-assump-aux* (*Polynomial.lead-coeff q*) *assumps*) *of*
None ⇒
let zero = *lc-assump-generation* (*one-less-degree q*) ((*Polynomial.lead-coeff q*, (*0*::*rat*)) # *assumps*);
one = ((*Polynomial.lead-coeff q*, (*1*::*rat*)) # *assumps*, *q*);
minus-one = ((*Polynomial.lead-coeff q*, (−*1*::*rat*)) # *assumps*, *q*) *in*
one#*minus-one*#*zero*
| (*Some i*) ⇒
(*if i* = *0 then lc-assump-generation* (*one-less-degree q*) *assumps*
else
[(*assumps*, *q*)]
)
))
by *auto*
termination apply (*relation* *measure* (λ(*q*, *assumps*). (*let w* = (*if q* ≠ *0 then 1 else 0*) *in w* + *Polynomial.degree q*)))
apply (*auto*) **using** *one-less-degree-degree*
apply (*smt* (*verit*, *del-insts*) *Multiv-Poly-Props.one-less-degree-def Polynomial.coeff-diff Polynomial.lead-coeff-monom cancel-comm-monoid-add-class.diff-cancel coeff-eq-0 degree-monom-eq leading-coeff-neq-0 linorder-neqE-nat*)
using *one-less-degree-degree*
by (*smt* (*verit*) *Multiv-Poly-Props.one-less-degree-def Polynomial.coeff-diff Polynomial.lead-coeff-monom cancel-comm-monoid-add-class.diff-cancel coeff-eq-0 degree-monom-eq leading-coeff-neq-0 linorder-neqE-nat*)

declare *lc-assump-generation.simps*[*simp del*]

value *lc-assump-generation* ([:*Var 1*:]::*rmpoly*) [(*Var 1*, *1*)]

fun *lc-assump-generation-list*:: *rmpoly list* ⇒ *assumps* ⇒ (*assumps* × *rmpoly list*) *list*
  where *lc-assump-generation-list* [] *assumps* = [(*assumps*, [])]
  | *lc-assump-generation-list* (*q*#*qs*) *assumps* = (*let rec* = *lc-assump-generation q assumps in*
    concat (*map* (
     λ(*new-assumps*, *r*). (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
      map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)) *rec*))

declare *lc-assump-generation-list.simps*[*simp del*]

value *lc-assump-generation-list* [([:*Var 1*:]::*rmpoly*), ([:*Var 1*:]::*rmpoly*)] []

value (*lc-assump-generation-list* [([:*Var 1*:]::*rmpoly*)] []) ! *1*

definition *poly-p*:: *rmpoly list* ⇒ *rmpoly*
  where *poly-p qs* = (*let prod-list* = *prod-list qs in*
    prod-list∗(*pderiv prod-list*))

primrec *check-all-const-deg-gen*:: ('*a*::*zero*) *Polynomial.poly list* ⇒ *bool*
  where *check-all-const-deg-gen* [] = *True*
 | *check-all-const-deg-gen* (*h*#*T*) = (*if Polynomial.degree h* = *0 then* (*check-all-const-deg-gen T*) *else False*)

primrec *prod-list-var-gen*:: ('*a*::*idom*) *list* ⇒ ('*a*::*idom*)
  where *prod-list-var-gen* [] = *1*
 | *prod-list-var-gen* (*h*#*T*) = (*if h* = *0 then* (*prod-list-var-gen T*) *else* (*h*∗ *prod-list-var-gen T*))

fun *poly-p-in-branch*:: (*assumps* × *rmpoly list*) ⇒ *rmpoly*
  where *poly-p-in-branch* (*assumps*, *qs*) =
 (*if* (*check-all-const-deg-gen qs* = *True*) *then* [:*0*, *1*:] *else*
  (*pderiv* (*prod-list-var-gen qs*)) ∗ (*prod-list-var-gen qs*)
)

fun *limit-points-on-branch*:: (*assumps* × *rmpoly list*) ⇒ (*rat list* × *rat list*)
  where *limit-points-on-branch* (*assumps*, *qs*) =
    (*map* (λ*q*. *if q* = *0 then 0 else* (*rat-of-int* ∘ *Sturm-Tarski.sign*) (*lookup-assump* (*Polynomial.lead-coeff q*) *assumps*)) *qs*,
     map (λ*q*. *if q* = *0 then 0 else* (*rat-of-int* ∘ *Sturm-Tarski.sign*) (*lookup-assump* (*Polynomial.lead-coeff q*) *assumps*)∗(−*1*)^(*Polynomial.degree q*)) *qs*)

fun *extract-signs*:: (*assumps* × *matrix-equation*) *list* ⇒ (*assumps* × *rat list list*) *list*
  where *extract-signs qs* = *map* (λ(*assumps*, (*mat* , (*subs*, *signs*))). (*assumps*, *signs*)) *qs*

```
fun sign-determination-inner:: rmpoly list ⇒ assumps ⇒ (assumps × rat list list)
list
  where sign-determination-inner qs assumps =
( let branches = lc-assump-generation-list qs assumps  in
concat (map (λbranch.
let poly-p-branch = poly-p-in-branch branch;
    (pos-limit-branch, neg-limit-branch) = limit-points-on-branch branch;
     calculate-data-branch = extract-signs (calculate-data-assumps-M poly-p-branch
(snd branch) (fst branch))
in map (λ(a, signs). (a, pos-limit-branch#neg-limit-branch#signs)) calculate-data-branch
) branches
))

fun extract-polys:: atom fm ⇒ real mpoly list
  where extract-polys (Atom (Less p)) = [p] |
    extract-polys (Atom (Leq p)) = [p] |
    extract-polys (Atom (Eq p)) = [p] |
    extract-polys (Atom (Neq p)) = [p] |
    extract-polys (TrueF) = [] |
    extract-polys (FalseF) = [] |
    extract-polys (And φ ψ) =  (extract-polys φ )@ (extract-polys ψ) |
    extract-polys (Or φ ψ) = (extract-polys φ)@(extract-polys ψ) |
    extract-polys (Neg φ)  = (extract-polys φ) |
    extract-polys (ExN 0 φ)  = (extract-polys φ) |
    extract-polys (AllN 0 φ)  = (extract-polys φ) |
    extract-polys -  = []


fun lookup-sem-M :: atom fm ⇒ (real mpoly × rat) list ⇒ bool option
  where
    lookup-sem-M TrueF ls = Some (True)
  | lookup-sem-M FalseF ls = Some (False)
  |  lookup-sem-M (And l r) ls = (case (lookup-sem-M l ls, lookup-sem-M r ls)
      of (Some i, Some j) ⇒ Some (i ∧ j)
      | - ⇒ None)
  | lookup-sem-M (Or l r) ls = (case (lookup-sem-M l ls, lookup-sem-M r ls)
      of (Some i, Some j) ⇒ Some (i ∨ j)
      | - ⇒ None)
  | lookup-sem-M (Neg l) ls = (case (lookup-sem-M l ls)
      of Some i ⇒ Some ((¬i))
      | - ⇒ None)
  | lookup-sem-M (Atom (Less p)) ls =
     (case (lookup-assump-aux p ls) of
     Some i ⇒ Some (i < 0)
    | - ⇒ None
     )
  | lookup-sem-M (Atom (Leq p)) ls =
     (case (lookup-assump-aux p ls) of
```

```
    Some i ⇒ Some (i ≤ 0)
   | - ⇒ None
    )
 | lookup-sem-M (Atom (Eq p)) ls =
    (case (lookup-assump-aux p ls) of
    Some i ⇒ Some (i = 0)
   | - ⇒ None
    )
 | lookup-sem-M (Atom (Neq p)) ls =
    (case (lookup-assump-aux p ls) of
    Some i ⇒ Some (i ≠ 0)
   | - ⇒ None
    )
 | lookup-sem-M (ExN 0 l) ls = lookup-sem-M l ls
 | lookup-sem-M (AllN 0 l) ls = lookup-sem-M l ls
 | lookup-sem-M - ls = None

fun assump-to-atom:: (real mpoly × rat) ⇒ atom
  where assump-to-atom (p, r) =
      (if r = 0 then (Eq p)
    else (if r < 0 then (Less p)
    else (Less (−p))
 ))

fun assump-to-atom-fm:: assumps ⇒ atom fm
  where assump-to-atom-fm [] = TrueF
 | assump-to-atom-fm ((p, r)#T) = And (Atom (assump-to-atom (p, r))) (assump-to-atom-fm
T)

fun create-disjunction:: (assumps × rat list list) list  ⇒ atom fm
  where create-disjunction [] = FalseF
 | create-disjunction ((a, -)#T) = Or (assump-to-atom-fm a) (create-disjunction
T)

fun elim-forall:: atom fm ⇒ atom fm
  where elim-forall F =
 (
   let qs = extract-polys F;
       univ-qs = univariate-in qs 0;
       reindexed-univ-qs = map (map-poly (lowerPoly 0 1)) univ-qs;
       data = sign-determination-inner reindexed-univ-qs [];
       new-data = filter (λ(assumps, signs-list).
         list-all (λ signs.
         let paired-signs = zip qs signs in
           lookup-sem-M F paired-signs = (Some True))
         signs-list
         ) data
 in create-disjunction new-data
 )
```

definition *elim-exist*:: *atom fm* ⇒ *atom fm*
where *elim-exist F* = *Neg* (*elim-forall* (*Neg F*))

fun *structural-complexity*:: *atom fm* ⇒ (*nat* × *nat*)
where
structural-complexity TrueF = (*0*, *1*)
| *structural-complexity FalseF* = (*0*, *1*)
| *structural-complexity* (*Atom a*) = (*0*, *1*)
| *structural-complexity* (*And F1 F2*) =
(*let* (*qF1*, *sF1*) = *structural-complexity F1*;
(*qF2*, *sF2*) = *structural-complexity F2*
in (*qF1* + *qF2*, *1* + *sF1* + *sF2*))
| *structural-complexity* (*Or F1 F2*) =
(*let* (*qF1*, *sF1*) = *structural-complexity F1*;
(*qF2*, *sF2*) = *structural-complexity F2*
in (*qF1* + *qF2*, *1* + *sF1* + *sF2*))
| *structural-complexity* (*Neg F*) =
(*let* (*qF*, *sF*) = *structural-complexity F*
in (*qF*, *1* + *sF*))
| *structural-complexity* (*ExQ F*) =
(*let* (*qF*, *sF*) = *structural-complexity F*
in (*1*+ *qF*, *1* + *sF*))
| *structural-complexity* (*AllQ F*) =
(*let* (*qF*, *sF*) = *structural-complexity F*
in (*1*+ *qF*, *1* + *sF*))
| *structural-complexity* (*ExN n F*) =
(*let* (*qF*, *sF*) = *structural-complexity F*
in (*2* + *n*+*qF*, *2*+*n*+*sF*))
| *structural-complexity* (*AllN n F*) =
(*let* (*qF*, *sF*) = *structural-complexity F*
in (*2* + *n*+*qF*, *2*+*n*+*sF*))

declare *structural-complexity.simps*[*simp del*]

fun *qe*:: *atom fm* ⇒ *atom fm*
where
qe TrueF = *TrueF*
| *qe FalseF* = *FalseF*
| *qe* (*Atom a*) = (*Atom a*)
| *qe* (*And F1 F2*) = *And* (*qe F1*) (*qe F2*)
| *qe* (*Or F1 F2*) = *Or* (*qe F1*) (*qe F2*)
| *qe* (*Neg F*) = *Neg* (*qe F*)
| *qe* (*ExQ F*) = *elim-exist* (*qe F*)
| *qe* (*AllQ F*) = *elim-forall* (*qe F*)
| *qe* (*AllN n F*) = (*elim-forall* ^^ *n*) (*qe F*)
| *qe* (*ExN n F*) = (*elim-exist* ^^ *n*) (*qe F*)

definition *qe-with-VS*:: *atom fm* ⇒ *atom fm*
where *qe-with-VS F* = (*qe* ∘ *VSLEG*) *F*

value ((*MPoly* (*Pm-fmap* (*fmap-of-list* [(*Pm-fmap* (*fmap-of-list* []), *1*)])))::*real mpoly*)
= *Const 1*

fun *eval-ground* :: *atom fm* ⇒ *real list* ⇒ *bool* **where**
eval-ground (*Atom a*) Γ = *aEval a* Γ |
eval-ground (*TrueF*) - = *True* |
eval-ground (*FalseF*) - = *False* |
eval-ground (*And* φ ψ) Γ = ((*eval-ground* φ Γ) ∧ (*eval-ground* ψ Γ)) |
eval-ground (*Or* φ ψ) Γ = ((*eval-ground* φ Γ) ∨ (*eval-ground* ψ Γ)) |
eval-ground (*Neg* φ) Γ = (¬ (*eval-ground* φ Γ))

value *VSLEG* (*ExQ* (*ExQ* (*Atom* (*Less* (*Var 0^2∗Var 1* ::*real mpoly*)))))
value (*qe-with-VS* (*ExQ* (*ExQ* (*Atom* (*Less* (*Var 0^2∗Var 1* ::*real mpoly*))))))

16 Decision Portion

fun *extract-polys-from-assumps*:: *assumps* ⇒ *real mpoly list*
where *extract-polys-from-assumps* [] = []
| *extract-polys-from-assumps* ((*p*, *i*)#*T*) = *p*#(*extract-polys-from-assumps T*)

fun *assumps-are-consistent*:: *assumps* ⇒ *rat list list* ⇒ *bool*
where *assumps-are-consistent assump ls* = ((*map snd assump*) ∈ *set ls*)

fun *find-consistent-signs-at-roots-single-M*:: (*assumps* × *matrix-equation*) ⇒ *rat list list*
where *find-consistent-signs-at-roots-single-M* (*assumps*, (*M*, (*subsets*, *signs*))) = *signs*

fun *find-consistent-signs-at-roots-M*:: (*assumps* × *matrix-equation*) *list* ⇒ *rat list list*
where *find-consistent-signs-at-roots-M l* = *concat* (*map find-consistent-signs-at-roots-single-M l*)

16.1 Limit Points and Helper Functions

definition *expand-signs-list*:: *real mpoly list* ⇒ *rat list list* ⇒ (*real mpoly* × *rat*) *list list*
where *expand-signs-list qs csas* = *map* (λ*csa*. *zip qs csa*) *csas*

fun *first-nonzero-coefficient-degree-helper*:: (*real mpoly* × *rat*) *list* ⇒ *real mpoly list*
⇒ *nat* ⇒ (*nat* × *rat*)
where *first-nonzero-coefficient-degree-helper assumps* [] *n* = (*n*, *0*)
| *first-nonzero-coefficient-degree-helper assumps* (*h* # *T*) *n* =
(*case lookup-assump-aux h assumps of*
(*Some i*) ⇒ (*if i* ≠ *0 then* (*n*, *i*) *else first-nonzero-coefficient-degree-helper*
assumps T (*n*−*1*))
| *None* ⇒ *first-nonzero-coefficient-degree-helper assumps T* (*n*−*1*))

fun *first-nonzero-coefficient-degree-helper-simp*:: (*real mpoly* × *rat*) *list* ⇒ *real mpoly*
list ⇒ (*nat* × *rat*)
where *first-nonzero-coefficient-degree-helper-simp assumps* [] = (*0*, *0*)
| *first-nonzero-coefficient-degree-helper-simp assumps* (*h* # *T*) =
(*case lookup-assump-aux h assumps of*
(*Some i*) ⇒ (*if i* ≠ *0 then* (*length T*, *i*) *else first-nonzero-coefficient-degree-helper-simp*
assumps T)
| *None* ⇒ *first-nonzero-coefficient-degree-helper-simp assumps T*)

lemma *first-nonzero-coefficient-degree-helper-simp*:
shows *first-nonzero-coefficient-degree-helper-simp assumps ell*
= *first-nonzero-coefficient-degree-helper assumps ell* (*length ell* − *1*)
proof (*induct ell*)
case *Nil*
then show *?case*
by *auto*
next
case (*Cons a ell*)
moreover {
assume ∗: *lookup-assump-aux a assumps* = *Some 0*
then have *first-nonzero-coefficient-degree-helper-simp assumps* (*a* # *ell*) =
first-nonzero-coefficient-degree-helper assumps (*a* # *ell*) (*length* (*a* # *ell*) −
1)
using *Cons.hyps*
by *simp*
}
moreover {
assume ∗: ∃ *k*≠*0*. *lookup-assump-aux a assumps* = *Some k*
then obtain *k* **where** *k-prop*: *k*≠*0* ∧ *lookup-assump-aux a assumps* = *Some k*
by *auto*
then have *first-nonzero-coefficient-degree-helper-simp assumps* (*a* # *ell*) =
first-nonzero-coefficient-degree-helper assumps (*a* # *ell*) (*length* (*a* # *ell*) −
1)
using *Cons.hyps*
by *simp*
}
moreover {
assume ∗: *lookup-assump-aux a assumps* = *None*
then have *first-nonzero-coefficient-degree-helper-simp assumps* (*a* # *ell*) =

```
      first-nonzero-coefficient-degree-helper assumps (a # ell) (length (a # ell) −
1)
    by (simp add: local.Cons)
  }
  ultimately have first-nonzero-coefficient-degree-helper-simp assumps (a # ell)
=
      first-nonzero-coefficient-degree-helper assumps (a # ell) (length (a # ell) −
1)
   by fastforce
  then show ?case by auto
qed

declare pull-out-pairs.simps [simp del]
declare construct-rhs-vector-rec-M.simps [simp del]

declare first-nonzero-coefficient-degree-helper.simps[simp del]
declare first-nonzero-coefficient-degree-helper-simp.simps[simp del]

definition sign-and-degree-of-first-nonzero-coefficient:: (real mpoly × rat) list ⇒
rmpoly ⇒ (nat × rat)
  where sign-and-degree-of-first-nonzero-coefficient assumps q =
   first-nonzero-coefficient-degree-helper assumps (rev (Polynomial.coeffs q)) ((length
(Polynomial.coeffs q)) − 1)

definition sign-and-degree-of-first-nonzero-coefficient-simp:: (real mpoly × rat) list
⇒ rmpoly ⇒ (nat × rat)
  where sign-and-degree-of-first-nonzero-coefficient-simp assumps q =
    first-nonzero-coefficient-degree-helper-simp assumps (rev (Polynomial.coeffs q))

lemma sign-and-degree-of-first-nonzero-coefficient-simp:
 sign-and-degree-of-first-nonzero-coefficient assumps q = sign-and-degree-of-first-nonzero-coefficient-simp
assumps q
  using first-nonzero-coefficient-degree-helper-simp
 by (simp add: sign-and-degree-of-first-nonzero-coefficient-def sign-and-degree-of-first-nonzero-coefficient-simp



definition sign-and-degree-of-first-nonzero-coefficient-list:: rmpoly list ⇒ (real mpoly
× rat) list ⇒ (nat × rat) list
  where sign-and-degree-of-first-nonzero-coefficient-list qs assumps =
    map (λq. sign-and-degree-of-first-nonzero-coefficient-simp assumps q) qs

fun all-pos-limit-points:: rmpoly list ⇒ rat list list ⇒ rat list list
  where all-pos-limit-points qs coeffs-signs  =
(if qs = [] then []
else (if (all-coeffs qs = []) then ([map (λx. 0) qs])
  else
  (let expand-coeffs-signs = expand-signs-list (all-coeffs qs) coeffs-signs in
  map ((map snd) ∘ sign-and-degree-of-first-nonzero-coefficient-list qs) expand-coeffs-signs)))
```

fun *all-neg-limit-points-aux*:: (*nat* × *rat*) *list* ⇒ *rat list*
where *all-neg-limit-points-aux deg-sign-list* = *map* (λ(*deg*, *sgn*). (−1)^*deg*∗*sgn*) *deg-sign-list*

fun *all-neg-limit-points*:: *rmpoly list* ⇒ *rat list list* ⇒ *rat list list*
where *all-neg-limit-points qs coeffs-signs* =
(*let expand-coeffs-signs* = *expand-signs-list* (*all-coeffs qs*) *coeffs-signs*;
(*sgn-and-deg-list*::(*nat* × *rat*) *list list*) = *map* (*sign-and-degree-of-first-nonzero-coefficient-list qs*) *expand-coeffs-signs*
in map all-neg-limit-points-aux sgn-and-deg-list)

16.2 Top-level functions QE

definition *transform*:: *real mpoly list* ⇒ *real mpoly Polynomial.poly list*
where *transform qs* = (*let vs* = *variables-list qs in*
map (λ*q*. (*mpoly-to-mpoly-poly-alt* (*nth vs* (*length vs* − 1)) *q*)) *qs*)

fun *calculate-data-to-signs*:: (*assumps* × *matrix-equation*) *list* ⇒ (*assumps* × *rat list list*) *list*
where *calculate-data-to-signs ell* = *map* (λ*x*. (*fst x*, *snd* (*snd* (*snd x*)))) *ell*

fun *sum-list*:: *nat list* ⇒ *nat*
where *sum-list* [] = *0*
| *sum-list* (*a* # *ell*) = *a* + (*sum-list ell*)

fun *limit-point-data*:: (*rat* × *nat*) *list* ⇒ (*rat list* × *rat list*)
where *limit-point-data ell* = (*map fst ell*, *map* (λ*x*. *fst x* ∗ (−1)^(*snd x*)) *ell*)

fun *generate-signs-and-assumptions*:: *rmpoly list* ⇒ (*assumps* × *rat list list*) *list*
where *generate-signs-and-assumptions qs-univ* =
(*let p* = *poly-p qs-univ*; *calc-data* = *calculate-data-M p qs-univ in* [])

export-code *calculate-data-assumps-M qe VSLEG add mult C V pow minus real-of-int real-mult real-plus real-minus real-div print-mpoly eval-ground*
in *SML* **module-name** *export*

end

theory *Multiv-Tarski-Query*
imports
Multiv-Pseudo-Remainder-Sequence
Hybrid-Multiv-Matrix

begin

definition *sign-rat*::'*a*::{*zero*,*linorder*} ⇒ *rat* **where**

sign-rat n = rat-of-int (Sturm-Tarski.sign n)

17 Connect multivariate Tarski queries to univariate

lemma *cast-sgn-same-map*:
shows *map of-rat (map sgn ell) = map sgn ell*
by *simp*

lemma *changes-cast-sgn-same-map*:
shows *changes ((map of-rat ell)::real list) = changes (ell::rat list)*
proof (*induct length ell arbitrary*: *ell rule*: *less-induct*)
case *less*
then have *indhyp*: ∀ *ell1*. *length ell1 < length ell* ⟶ *changes (map real-of-rat ell1) = changes ell1*
by *blast*
{
assume ∗: *length ell = 0*
then have *changes (map real-of-rat ell) = changes ell*
by *auto*
}
moreover {
assume ∗: *length ell = 1*
then have ∃ *h*. *ell = [h]*
by (*simp add*: *length-Suc-conv*)
then have *changes (map real-of-rat ell) = changes ell*
by *auto*
}
moreover {
assume ∗: *length ell > 1*
then have ∃ *elem1 elem2 ell1*. *ell = elem1 # (elem2 # ell1)*
by (*metis One-nat-def Suc-le-length-iff le-simps(1) length-Cons less-Suc-eq-le*)
then obtain *elem1 elem2 ell1* **where** *ell-prop*: *ell = elem1 # (elem2 # ell1)*
by *auto*
have *len-lt*: *length (elem1 # ell1) < length ell*
by (*simp add*: *ell-prop*)
then have *h1*: *changes (map real-of-rat (elem1 # ell1)) = changes (elem1 # ell1)*
using *indhyp*
by *blast*
have *h2*: *changes (map real-of-rat (elem2 # ell1)) = changes (elem2 # ell1)*
using *indhyp*
by (*metis len-lt list.size(4)*)
have *h3*: *real-of-rat elem1 ∗ real-of-rat elem2 < 0* ⟹ *elem2 ≠ 0* ⟹ *elem1 ∗ elem2 < 0*
by (*metis of-rat-less-0-iff of-rat-mult*)
have *h4*: ¬ *real-of-rat elem1 ∗ real-of-rat elem2 < 0* ⟹ *elem2 ≠ 0* ⟹ *elem1 ∗ elem2 < 0* ⟹ *False*

by (*metis of-rat-less-0-iff of-rat-mult*)
have *changes* (*map real-of-rat* (*elem1* # (*elem2* # *ell1*))) = *changes* (*elem1* # (*elem2* # *ell1*))
using *h1 h2 h3 h4* **by** *auto*
then have *changes* (*map real-of-rat ell*) = *changes ell*
using *ell-prop* **by** *auto*
}
ultimately show *?case*
by (*meson less-one linorder-neqE-nat*)
qed

lemma *spmods-multiv-lc-auxNone*:
assumes *inset*: (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv p q acc*)
assumes *pnonz*: *p* ≠ *0*
assumes *lookup-none*: (*lookup-assump-aux* (*Polynomial.lead-coeff p*) *acc*) = *None*
shows (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv* (*one-less-degree p*) *q* ((*Polynomial.lead-coeff p*, (*0*::*rat*)) # *acc*))
∨ (∃ *k* ≠ *0*. (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, *k*) # *acc*)))
proof −
have (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv* (*one-less-degree p*) *q* ((*Polynomial.lead-coeff p*, (*0*::*rat*)) # *acc*))
∨ ((*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (*1*::*rat*)) # *acc*))) ∨
(*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (−*1*::*rat*)) # *acc*))
using *lookup-none inset pnonz spmods-multiv.simps*[*of p q acc*]
by *auto*
then show *?thesis*
using *class-field.zero-not-one class-field.neg-1-not-0*
by *metis*
qed

lemma *spmods-multiv-lc-auxSome1*:
assumes *inset*: (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv p q acc*)
assumes *pnonz*: *p* ≠ *0*
assumes *lookup-some*: (*lookup-assump-aux* (*Polynomial.lead-coeff p*) *acc*) = *Some 0*
shows (((*Polynomial.lead-coeff p*), *0*) ∈ *set acc* ∧ (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv* (*one-less-degree p*) *q acc*))
using *assms spmods-multiv.simps*[*of p q acc*]
using *lookup-assum-aux-mem option.simps*(*5*) **by** *fastforce*

lemma *spmods-multiv-lc-auxSome2*:
assumes *inset*: (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv p q acc*)
assumes *pnonz*: *p* ≠ *0*
assumes *lookup-some*: (*lookup-assump-aux* (*Polynomial.lead-coeff p*) *acc*) = *Some i* ∧ *i* ≠ *0*
shows (∃ *k* ≠ *0*. (((*Polynomial.lead-coeff p*), *k*) ∈ *set acc* ∧ (*assumps*, *sturm-seq*)

$\in$ *set* (*spmods-multiv-aux p q acc*)))
using *assms spmods-multiv.simps*[*of p q acc*] *lookup-assum-aux-mem*
by (*smt* (*verit*, *best*) *option.simps*(*5*))

lemma *spmods-multiv-lc-aux*:
assumes *inset*: (*assumps*, *sturm-seq*) $\in$ *set* (*spmods-multiv p q acc*)
assumes *pnonz*: $p \neq 0$
shows ($\exists$ *accum*. (((*Polynomial.lead-coeff p*), *0*) $\in$ *set accum* $\wedge$ (*assumps*, *sturm-seq*)
$\in$ *set* (*spmods-multiv* (*one-less-degree p*) *q accum*)))
$\vee$ ($\exists$ *accum*. ($\exists$ *k* $\neq$ *0*. ((((*Polynomial.lead-coeff p*), *k*) $\in$ *set accum*) $\wedge$ (*assumps*,
sturm-seq) $\in$ *set* (*spmods-multiv-aux p q accum*))))
proof −
have (*lookup-assump-aux* (*Polynomial.lead-coeff p*) *acc*) = *None* $\vee$ ($\exists$ *k*. (*lookup-assump-aux*
(*Polynomial.lead-coeff p*) *acc*) = *Some k*)
by *auto*
{assume $*$: (*lookup-assump-aux* (*Polynomial.lead-coeff p*) *acc*) = *None*
then have ($\exists$ *accum*. (((*Polynomial.lead-coeff p*), *0*) $\in$ *set accum* $\wedge$ (*assumps*,
sturm-seq) $\in$ *set* (*spmods-multiv* (*one-less-degree p*) *q accum*)))
$\vee$ ($\exists$ *accum*. ($\exists$ *k* $\neq$ *0*. ((((*Polynomial.lead-coeff p*), *k*) $\in$ *set accum*) $\wedge$ (*assumps*,
sturm-seq) $\in$ *set* (*spmods-multiv-aux p q accum*))))
using *spmods-multiv-lc-auxNone*
by (*meson inset list.set-intros*(*1*) *pnonz*)
} moreover {assume $*$: ($\exists$ *k*. (*lookup-assump-aux* (*Polynomial.lead-coeff p*) *acc*)
= *Some k*)
then have ($\exists$ *accum*. (((*Polynomial.lead-coeff p*), *0*) $\in$ *set accum* $\wedge$ (*assumps*,
sturm-seq) $\in$ *set* (*spmods-multiv* (*one-less-degree p*) *q accum*)))
$\vee$ ($\exists$ *accum*. ($\exists$ *k* $\neq$ *0*. ((((*Polynomial.lead-coeff p*), *k*) $\in$ *set accum*) $\wedge$ (*assumps*,
sturm-seq) $\in$ *set* (*spmods-multiv-aux p q accum*))))
using *spmods-multiv-lc-auxSome2*
by (*metis inset pnonz spmods-multiv-lc-auxSome1*)
} moreover {assume $*$: (*lookup-assump-aux* (*Polynomial.lead-coeff p*) *acc*) =
Some 0
then have ($\exists$ *accum*. (((*Polynomial.lead-coeff p*), *0*) $\in$ *set accum* $\wedge$ (*assumps*,
sturm-seq) $\in$ *set* (*spmods-multiv* (*one-less-degree p*) *q accum*)))
$\vee$ ($\exists$ *accum*. ($\exists$ *k* $\neq$ *0*. ((((*Polynomial.lead-coeff p*), *k*) $\in$ *set accum*) $\wedge$ (*assumps*,
sturm-seq) $\in$ *set* (*spmods-multiv-aux p q accum*))))
by (*metis inset pnonz spmods-multiv-lc-auxSome1*)
}
ultimately show *?thesis*
by *blast*
qed

lemma *spmods-multiv-lc*:
assumes *inset*: (*assumps*, *sturm-seq*) $\in$ *set* (*spmods-multiv p q acc*)
assumes *lc-inset*: *lc* $\in$ *set* (*lead-coeffs sturm-seq*)
shows$\exists$ *r*. (*lc*,*r*) $\in$ *set assumps* $\wedge$ *r* $\neq$ *0*
using *assms*
proof (*induct p q acc arbitrary*:*assumps sturm-seq lc rule*: *spmods-multiv.induct*)

```
  case ih: (1 p q acc)
  have p = 0 ∨ p ≠ 0 by auto
  moreover {
    assume ∗: p = 0
    then have sturm-seq = []
      using ih.prems(1) spmods-multiv.simps by fastforce
    then have set (lead-coeffs sturm-seq) = {} by auto
    then have False
      using ih.prems(2) by force
  }
  moreover {
    assume ∗: p ≠ 0
    moreover {
      assume ∗∗: (lookup-assump-aux (Polynomial.lead-coeff p) acc) = None
       then have (assumps, sturm-seq) ∈ set (spmods-multiv (one-less-degree p) q
((Polynomial.lead-coeff p, (0::rat)) # acc))
   ∨ (∃ k ≠ 0. (assumps, sturm-seq) ∈ set (spmods-multiv-aux p q ((Polynomial.lead-coeff
p, k) # acc)))
        using ∗ spmods-multiv-lc-auxNone[of assumps sturm-seq p q acc]
          ih(3) by auto
      moreover {
        assume eo: (assumps, sturm-seq) ∈ set (spmods-multiv (one-less-degree p)
q ((Polynomial.lead-coeff p, (0::rat)) # acc))
        then have ∃ r. (lc,r) ∈ set assumps ∧ r ≠ 0
          using ih ∗ ∗∗ by blast
      }
      moreover {
        assume eo: (∃ k ≠ 0. (assumps, sturm-seq) ∈ set (spmods-multiv-aux p q
((Polynomial.lead-coeff p, k) # acc)))
          then obtain k where k-prop: k ≠ 0 ∧ (assumps, sturm-seq) ∈ set
(spmods-multiv-aux p q ((Polynomial.lead-coeff p, k) # acc))
          by auto
        then have ∃ r. (lc,r) ∈ set assumps ∧ r ≠ 0
          using ∗ spmods-multiv-aux-sturm-lc[of p k ((Polynomial.lead-coeff p, k) #
acc) assumps sturm-seq q] lc-inset
          using ih.prems(2) by auto
      }
      ultimately have ∃ r. (lc,r) ∈ set assumps ∧ r ≠ 0
        by blast
    }
    moreover {
      assume ∗∗: ∃ i. (lookup-assump-aux (Polynomial.lead-coeff p) acc) = Some i
       then obtain i where i-prop: (lookup-assump-aux (Polynomial.lead-coeff p)
acc) = Some i
        by auto
      moreover {
        assume i: i = 0
       then have (((Polynomial.lead-coeff p), 0) ∈ set acc  ∧ (assumps, sturm-seq)
∈ set (spmods-multiv (one-less-degree p) q acc))
```

using ∗ *i-prop spmods-multiv-lc-auxSome1*[*of assumps sturm-seq p q acc*] *ih*(*3*)
by *auto*
then have ∃ *r*. (*lc*,*r*) ∈ *set assumps* ∧ *r* ≠ *0* **using** ∗ *ih*(*4*) *i-prop i*
ih(*2*)[*of i assumps sturm-seq lc*] **by** *auto*
}
moreover {
assume *i*: *i* ≠ *0*
then have *h1*: (∃ *accum*. (∃ *k* ≠ *0*. ((((*Polynomial.lead-coeff p*), *k*)) ∈ *set accum* ∧ (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q accum*))))
using ∗ *i-prop spmods-multiv-lc-auxSome2*[*of assumps sturm-seq p q acc*] *ih*(*3*)
by *auto*
then have ∃ *r*. (*lc*,*r*) ∈ *set assumps* ∧ *r* ≠ *0*
using *spmods-multiv-aux-sturm-lc*[*of p i acc assumps sturm-seq*]
proof −
have *f1*: ∀ *p r ps psa psb pa pb*. ((*Polynomial.lead-coeff p*, *r*) ∉ *set ps* ∨ *r* = *0* ∨ (*psa*, *psb*) ∉ *set* (*spmods-multiv-aux p pa ps*) ∨ *pb* ∉ *set psb*) ∨ (∃ *r*. (*Polynomial.lead-coeff pb*, *r*) ∈ *set psa* ∧ *r* ≠ *0*)
using *spmods-multiv-aux-sturm-lc* **by** *blast*
obtain *rr* :: *real mpoly Polynomial.poly* ⇒ (*real mpoly* × *rat*) *list* ⇒ *rat* **where**
∀ *x0 x3*. (∃ *v7*. (*Polynomial.lead-coeff x0*, *v7*) ∈ *set x3* ∧ *v7* ≠ *0*) = ((*Polynomial.lead-coeff x0*, *rr x0 x3*) ∈ *set x3* ∧ *rr x0 x3* ≠ *0*)
by *moura*
then have *f2*: ∀ *p r ps psa psb pa pb*. ((*Polynomial.lead-coeff p*, *r*) ∉ *set ps* ∨ *r* = *0* ∨ (*psa*, *psb*) ∉ *set* (*spmods-multiv-aux p pa ps*) ∨ *pb* ∉ *set psb*) ∨ (*Polynomial.lead-coeff pb*, *rr pb psa*) ∈ *set psa* ∧ *rr pb psa* ≠ *0*
using *f1* **by** *presburger*
obtain *pp* :: *real mpoly Polynomial.poly set* ⇒ (*real mpoly Polynomial.poly* ⇒ *real mpoly*) ⇒ *real mpoly* ⇒ *real mpoly Polynomial.poly* **where**
f3: ∀ *x0 x1 x2*. (∃ *v3*. *x2* = *x1 v3* ∧ *v3* ∈ *x0*) = (*x2* = *x1* (*pp x0 x1 x2*) ∧ *pp x0 x1 x2* ∈ *x0*)
by *moura*
have *lc* ∈ *Polynomial.lead-coeff* ‘ *set sturm-seq*
by (*smt* (*z3*) *ih.prems*(*2*) *list.set-map*)
then have *f4*: *lc* = *Polynomial.lead-coeff* (*pp* (*set sturm-seq*) *Polynomial.lead-coeff lc*) ∧ *pp* (*set sturm-seq*) *Polynomial.lead-coeff lc* ∈ *set sturm-seq*
using *f3* **by** (*meson imageE*)
then have (*Polynomial.lead-coeff* (*pp* (*set sturm-seq*) *Polynomial.lead-coeff lc*), *rr* (*pp* (*set sturm-seq*) *Polynomial.lead-coeff lc*) *assumps*) ∈ *set assumps* ∧ *rr* (*pp* (*set sturm-seq*) *Polynomial.lead-coeff lc*) *assumps* ≠ *0*
using *f2* **by** (*meson h1*)
then show *?thesis*
using *f4* **by** *auto*
qed
}
ultimately have ∃ *r*. (*lc*,*r*) ∈ *set assumps* ∧ *r* ≠ *0*
by *blast*

```
    }
    ultimately have ∃ r. (lc,r) ∈ set assumps ∧ r ≠ 0
      by blast
  }
  ultimately show ?case by blast
qed

lemma map-eq-2:
  assumes ∀ i < n.  f i = g i
  shows map (λi. f i) [0..<n] =  map (λi. g i) [0..<n]
  by (simp add: assms)

lemma changes-eq:
  shows changes q = changes (map real-of-int q)
proof (induct length q arbitrary: q)
  case 0
  then show ?case by auto
next
  case (Suc x)
  then have ind: ∀ q. x = length q ⟶ changes q = changes (map real-of-int q)
    by auto
  have  Suc x = length q
    using Suc.hyps(2) by blast
  have x-zer: x = 0 ⟹  changes q = changes (map real-of-int q)
  proof −
    assume x = 0
    then have ∃ a. q = [a]
      using Suc.hyps(2)
      by (metis length-Suc-conv nat.distinct(1) remdups-adj.cases)
    then obtain a where a-prop: q = [a] by auto
    have changes [a] = changes (map real-of-int [a]) by auto
    then show changes q = changes (map real-of-int q)
      using a-prop by auto
  qed
  have x-nonz: x ≠ 0 ⟹  changes q = changes (map real-of-int q)
  proof −
    assume x ≠ 0
    then have ∃ a b c. q = a#b#c
      using Suc.hyps(2)
      by (metis Suc-length-conv list-decode.cases)
    then obtain a b c where abc-prop: q = a#b#c by auto
    have changes (a#b#c) = changes (map real-of-int (a#b#c))
      apply (auto)
      using Suc.hyps(1) Suc.hyps(2) abc-prop apply force
        apply (simp add: mult-less-0-iff)
       apply (simp add: Suc.hyps(1) Suc.hyps(2) Suc-inject abc-prop)
      apply (metis of-int-less-0-iff of-int-mult)
      by (simp add: Suc.hyps(1) Suc.hyps(2) Suc-inject abc-prop)
    then show changes q = changes (map real-of-int q)
```

using *abc-prop* **by** *auto*
qed
then show *?case* **using** *x-zer x-nonz* **by** *auto*
qed

lemma *eval-mpoly-commutes-helper*:
assumes *val-sat*: $\bigwedge p\ n.\ (p,n) \in set\ assumps \Longrightarrow satisfies\text{-}evaluation\ val\ p\ n$
assumes *inset*: $(assumps, sturm\text{-}seq) \in set\ (spmods\text{-}multiv\ p\ q\ acc)$
shows $i < length\ sturm\text{-}seq \Longrightarrow eval\text{-}mpoly\ val\ (Polynomial.lead\text{-}coeff\ (sturm\text{-}seq\ !\ i)) = Polynomial.lead\text{-}coeff\ (eval\text{-}mpoly\text{-}poly\ val\ (sturm\text{-}seq\ !\ i))$
proof −
fix *i*
assume *i-lt*: $i < length\ sturm\text{-}seq$
have *s1*: $eval\text{-}mpoly\ val\ (map\ Polynomial.lead\text{-}coeff\ sturm\text{-}seq\ !\ i) = eval\text{-}mpoly\ val\ (Polynomial.lead\text{-}coeff\ (sturm\text{-}seq\ !\ i))$
by (*simp add*: *i-lt*)
have *s2*: $Polynomial.lead\text{-}coeff\ (map\ (eval\text{-}mpoly\text{-}poly\ val)\ sturm\text{-}seq\ !\ i) = Polynomial.lead\text{-}coeff\ (eval\text{-}mpoly\text{-}poly\ val\ (sturm\text{-}seq\ !\ i))$
using *i-lt* **by** *force*
let *?ssi* = $(sturm\text{-}seq\ !\ i)$
have $Polynomial.lead\text{-}coeff\ (sturm\text{-}seq\ !\ i) \in set\ (lead\text{-}coeffs\ sturm\text{-}seq)$
using *i-lt* **by** *force*
then have *ex-s*: $\exists s \neq 0.\ (Polynomial.lead\text{-}coeff\ ?ssi,\ s) \in set\ assumps$
using *spmods-multiv-aux-sturm-lc*
by (*metis* (*no-types*, *lifting*) *inset spmods-multiv-lc*)
then have $eval\text{-}mpoly\ val\ (Polynomial.lead\text{-}coeff\ ?ssi) \neq 0$
using *val-sat*[*of Polynomial.lead-coeff* $(sturm\text{-}seq\ !\ i)\ 0$]
unfolding *satisfies-evaluation-def*
using *satisfies-evaluation-nonzero val-sat* **by** *blast*
then show $eval\text{-}mpoly\ val\ (Polynomial.lead\text{-}coeff\ ?ssi) = Polynomial.lead\text{-}coeff\ (eval\text{-}mpoly\text{-}poly\ val\ ?ssi)$
by (*metis ex-s degree-valuation eval-mpoly-map-poly-comm-ring-hom.base.coeff-map-poly-hom eval-mpoly-poly-def val-sat*)
qed

lemma *changes-R-smods-multiv-connect-aux*:
assumes *inset*: $(assumps, sturm\text{-}seq) \in set\ (spmods\text{-}multiv\ p\ q\ acc)$
assumes *degree-list*: $degree\text{-}list = degrees\ sturm\text{-}seq$

assumes *signs-list*: $signs\text{-}list \in mpoly\text{-}consistent\text{-}sign\text{-}vectors\ (lead\text{-}coeffs\ sturm\text{-}seq)\ (all\text{-}lists\ (length\ val))$

assumes *val-sat*: $\forall\ p\ n.\ ((p,n) \in set\ assumps \longrightarrow satisfies\text{-}evaluation\ val\ p\ n)$

assumes *key*: $signs\text{-}list = map\ (\lambda x.\ sign\text{-}rat\ (eval\text{-}mpoly\ val\ x))\ (lead\text{-}coeffs\ sturm\text{-}seq)$
shows $changes\text{-}R\text{-}smods\text{-}multiv\ signs\text{-}list\ degree\text{-}list = changes\text{-}R\text{-}smods\text{-}multiv\text{-}val\ sturm\text{-}seq\ val$

proof −
let *?eval-ss* = *eval-mpoly-poly-list val sturm-seq*
have *signs-list* ∈ (*map-mpoly-sign* (*lead-coeffs sturm-seq*)) ‘ {(*ls*::*real list*). *length ls* = *length val*}
using *signs-list* **unfolding** *mpoly-consistent-sign-vectors-def all-lists-def*
by *auto*
then have ∃ *l* ∈{(*ls*::*real list*). *length ls* = *length val*}. *signs-list* = *map-mpoly-sign* (*lead-coeffs sturm-seq*) *l*
by *auto*
then obtain *l*::*real list* **where** *l-prop*: *length l* = *length val* ∧ *signs-list* = *map-mpoly-sign* (*lead-coeffs sturm-seq*) *l*
by *auto*
then have *l1*: *length signs-list* = *length sturm-seq*
unfolding *map-mpoly-sign-def* **by** *auto*
have *l2*: *length degree-list* = *length sturm-seq*
using *degree-list* **by** *auto*
have *len-eq*: *length degree-list* = *length signs-list* ∧ *length sturm-seq* = *length signs-list*
using *l1 l2* **by** *auto*
have *same-len*: *length degree-list* = *length signs-list*
using *l1 l2* **by** *auto*
have *sminus*: *sminus degree-list signs-list* = *changes-poly-neg-inf ?eval-ss*
proof −
have *len-eq2*: *length* (*eval-mpoly-poly-list val sturm-seq*) = *length degree-list*
using *l2* **unfolding** *eval-mpoly-poly-list-def*
by *auto*
have *dhelp*:⋀*i*. *i* < *length degree-list* ⟹ (*sgn* (*signs-list* ! *i*)) = *sgn* ((*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*))::*real*)
proof −
fix *i*
assume *i-lt*: *i* < *length degree-list*
have (*signs-list* ! *i*) = *sign-rat* (*eval-mpoly val* ((*lead-coeffs sturm-seq*) ! *i*))
using *signs-list*
using *i-lt len-eq*
by (*metis* (*no-types*, *lifting*) *key length-map nth-map*)
then have *h1*: (*sgn* (*signs-list* ! *i*)) = *sign-rat* (*eval-mpoly val* ((*lead-coeffs sturm-seq*) ! *i*))
by (*simp add*: *Sturm-Tarski.sign-def sign-rat-def*)
have *helper1*: *sign-rat* (*eval-mpoly val* ((*lead-coeffs sturm-seq*) ! *i*)) = *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff* (*sturm-seq* ! *i*)))
using *i-lt len-eq* **by** *auto*
have *helper2*: *sign-rat* (*Polynomial.lead-coeff* (*map* (*map-poly* (*eval-mpoly val*)) *sturm-seq* ! *i*)) = *sign-rat* (*Polynomial.lead-coeff* (*eval-mpoly-poly val* (*sturm-seq* ! *i*)))
using *i-lt eval-mpoly-poly-def eval-mpoly-poly-list-def len-eq2* **by** *force*
have *helper3*: *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff* (*sturm-seq* ! *i*))) = *sign-rat* (*Polynomial.lead-coeff* (*eval-mpoly-poly val* (*sturm-seq* ! *i*)))
using *val-sat inset eval-mpoly-commutes-helper*
by (*metis i-lt len-eq*)

then have *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff* (*sturm-seq* ! *i*))) = *sign-rat* ((*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*))::*real*)
unfolding *eval-mpoly-poly-list-def eval-mpoly-poly-def*
by (*simp add*: *helper2 helper3*)
then have (*of-rat* ∘ *sign-rat*) (*eval-mpoly val* (*Polynomial.lead-coeff* (*sturm-seq* ! *i*))) = *sgn* ((*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*))::*real*)
using *sgn-sign-eq*
by (*simp add*: *Sturm-Tarski.sign-def sgn-real-def sign-rat-def*)
then have (*of-rat* ∘ *sign-rat*) (*eval-mpoly val* ((*lead-coeffs sturm-seq*) ! *i*)) = *sgn* ((*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*))::*real*)
by (*simp add*: *helper1*)
then show (*sgn* (*signs-list* ! *i*)) = *sgn* ((*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*))::*real*)
using *h1 of-int-hom.hom-one of-int-minus sign-rat-def*
by (*smt* (*z3*) *comp-eq-dest-lhs of-rat-0 of-rat-1 of-rat-neg-one of-real-0 of-real-1 of-real-minus sgn-if*)
qed
have *dhelp2*: ⋀*i*. *i* < *length degree-list* ⟹ *Polynomial.degree* (*eval-mpoly-poly-list val sturm-seq* ! *i*) = *Polynomial.degree* (*sturm-seq* ! *i*)
proof −
fix *i*
assume *i* < *length degree-list*
then have *i-lt*: *i* < *length sturm-seq* **using** *len-eq* **by** *auto*
then have *s1*: *eval-mpoly val* (*map Polynomial.lead-coeff sturm-seq* ! *i*) = *eval-mpoly val* (*Polynomial.lead-coeff* (*sturm-seq* ! *i*))
by *simp*
have *s2*: *Polynomial.lead-coeff* (*map* (*eval-mpoly-poly val*) *sturm-seq* ! *i*) = *Polynomial.lead-coeff* (*eval-mpoly-poly val* (*sturm-seq* ! *i*))
using *i-lt* **by** *force*
let *?ssi* = (*sturm-seq* ! *i*)
have *Polynomial.lead-coeff* (*sturm-seq* ! *i*) ∈ *set* (*lead-coeffs sturm-seq*)
using *i-lt* **by** *force*
then have ∃ *k*≠*0*. (*Polynomial.lead-coeff ?ssi*, *k*) ∈ *set assumps*
using *spmods-multiv-lc*[*of assumps sturm-seq p q acc Polynomial.lead-coeff* (*sturm-seq* ! *i*)] *inset*
by *blast*
then have *eval-mpoly val* (*Polynomial.lead-coeff ?ssi*) ≠ *0*
using *val-sat* **unfolding** *satisfies-evaluation-def*
using *satisfies-evaluation-nonzero val-sat* **by** *blast*
then show *Polynomial.degree* (*eval-mpoly-poly-list val sturm-seq* ! *i*) = *Polynomial.degree* (*sturm-seq* ! *i*)
unfolding *eval-mpoly-poly-list-def eval-mpoly-poly-def*
by (*metis* (*no-types*, *lifting*) *Ring-Hom-Poly.degree-map-poly i-lt degree-0 map-poly-0 nth-map*)
qed
have *d1*: ⋀*i*. *even* (*Polynomial.degree* (*eval-mpoly-poly-list val sturm-seq* ! *i*)) ⟹
i < *length degree-list* ⟹
(*sgn* ((− *1*) ^ *degree-list* ! *i* ∗ *signs-list* ! *i*)) = *sgn* (*Polynomial.lead-coeff*

(*eval-mpoly-poly-list val sturm-seq* ! *i*))
proof −
fix *i*
assume *even*: *even* (*Polynomial.degree* (*eval-mpoly-poly-list val sturm-seq* ! *i*))
assume *i-lt-deg*: *i* < *length degree-list*
have *ev*: *even* (*degree-list* ! *i*)
using *dhelp2 even degree-list*
using *i-lt-deg* **by** *auto*
then show (*sgn* ((− *1*) ^ *degree-list* ! *i* ∗ *signs-list* ! *i*)) = *sgn* (*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*))
using *dhelp ev i-lt-deg*
by *simp*
qed
have *d2*: ⋀*i*. *odd* (*Polynomial.degree* (*eval-mpoly-poly-list val sturm-seq* ! *i*)) ⟹
i < *length degree-list* ⟹
of-rat (*sgn* ((− *1*) ^ *degree-list* ! *i* ∗ *signs-list* ! *i*)) = − *sgn* (*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*))
proof −
fix *i*
assume *odd*: *odd* (*Polynomial.degree* (*eval-mpoly-poly-list val sturm-seq* ! *i*))
assume *i-lt-deg*: *i* < *length degree-list*
have *odd1*: *odd* (*degree-list* ! *i*)
using *dhelp2 odd degree-list*
using *i-lt-deg* **by** *auto*
then have (*sgn* ((− *1*) ^ *degree-list* ! *i* ∗ *signs-list* ! *i*)) = − *sgn* (*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*))
using *dhelp odd*
by (*simp add*: *i-lt-deg of-rat-hom.hom-uminus*)
then show *real-of-rat* (*sgn* ((− *1*) ^ *degree-list* ! *i* ∗ *signs-list* ! *i*)) =
− *sgn* (*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*))
by (*smt* (*verit*, *ccfv-SIG*) *of-rat-0 of-rat-1 of-rat-neg-one of-real-0 of-real-1 of-real-eq-iff of-real-minus sgn-rat-def*)
qed
have ∀ *i* < *length degree-list*. (*of-rat* ((*sgn* ((− *1*) ^ *degree-list* ! *i* ∗ *signs-list* ! *i*))) =
sgn (*if even* (*Polynomial.degree* ((*eval-mpoly-poly-list val sturm-seq*)!*i*)) *then sgn* (*Polynomial.lead-coeff* ((*eval-mpoly-poly-list val sturm-seq*)!*i*)) *else* − *sgn* (*Polynomial.lead-coeff* ((*eval-mpoly-poly-list val sturm-seq*)!*i*))))
using *d1 d2*
by (*smt* (*verit*) *minus-of-real-eq-of-real-iff of-rat-0 of-rat-1 of-rat-hom.eq-iff of-real-0 of-real-1 real-of-rat-sgn sgn-real-def*)
then have *map of-rat* (*map* (λ*i*. (*sgn* ((− *1*) ^ *degree-list* ! *i* ∗ *signs-list* ! *i*))) [*0*..<*length degree-list*]) =
map
(λ*i*. *sgn* (*if even* (*Polynomial.degree* ((*eval-mpoly-poly-list val sturm-seq*)!*i*)) *then sgn* (*Polynomial.lead-coeff* ((*eval-mpoly-poly-list val sturm-seq*)!*i*)) *else* − *sgn* (*Polynomial.lead-coeff* ((*eval-mpoly-poly-list val sturm-seq*)!*i*))))

```
    [0..< length degree-list]
   using map-eq-2 add.left-neutral length-map map-upt nth-map nth-upt of-int-minus
    by auto
  then have map of-rat (map sgn ((map (λi. ((− 1) ^ degree-list ! i * signs-list
! i)) [0..<length degree-list]))) =
   (map sgn
   (map (λi. if even (Polynomial.degree ((eval-mpoly-poly-list val sturm-seq)!i))
      then sgn (Polynomial.lead-coeff ((eval-mpoly-poly-list val sturm-seq)!i)) else
          − sgn (Polynomial.lead-coeff ((eval-mpoly-poly-list val sturm-seq)!i)))
      [0..< length degree-list])::real list)
    by auto
 then have h1:map of-rat (map sgn ((map (λi. ((− 1) ^ degree-list ! i * signs-list
! i)) [0..<length degree-list]))) =
   map sgn
   (map (λi. if even (Polynomial.degree ((eval-mpoly-poly-list val sturm-seq)!i))
      then sgn (Polynomial.lead-coeff ((eval-mpoly-poly-list val sturm-seq)!i)) else
          − sgn (Polynomial.lead-coeff ((eval-mpoly-poly-list val sturm-seq)!i)))
      [0..< length (eval-mpoly-poly-list val sturm-seq)])
    using len-eq2
    by presburger
 have h2: (map (λi. if even (Polynomial.degree ((eval-mpoly-poly-list val sturm-seq)!i))

      then sgn (Polynomial.lead-coeff ((eval-mpoly-poly-list val sturm-seq)!i)) else
          − sgn (Polynomial.lead-coeff ((eval-mpoly-poly-list val sturm-seq)!i)))
      [0..< length (eval-mpoly-poly-list val sturm-seq)]) =
     (map (λp. if even (Polynomial.degree p)
       then sgn (Polynomial.lead-coeff p) else
          − sgn (Polynomial.lead-coeff p))
     (eval-mpoly-poly-list val sturm-seq))
    using map-upt by fastforce
   let ?m1 = ((map (λi. ((− 1) ^ degree-list ! i * signs-list ! i)) [0..<length
degree-list]))
 let ?m2 = ((map (λp. if even (Polynomial.degree p) then sgn (Polynomial.lead-coeff
p) else − sgn (Polynomial.lead-coeff p))
      (eval-mpoly-poly-list val sturm-seq)))::real list
   have map of-rat ((map sgn ?m1)::rat list) = ((map sgn ?m2)::real list)
    unfolding changes-poly-neg-inf-def sgn-neg-inf-def
    using h1 h2
    by presburger
 then have c1: changes ((map of-rat(map sgn ?m1))::real list) = changes ((map
sgn ?m2)::real list)
    using arg-cong
    by auto

   have c2: changes (map sgn ?m1) = changes ?m1
    using changes-map-sgn-eq[of ?m1] changes-eq
    by auto
   have c3: changes (map sgn ?m2::real list) = changes ?m2
    using changes-map-sgn-eq[of ?m2] changes-eq
```

by *auto*
have *c0*: *changes* (*map* (*real-of-rat* ∘ *sgn*) *?m1*) = *changes* (*map sgn ?m1*)
using *changes-cast-sgn-same-map*
by (*metis list.map-comp*)
then have *changes ?m1* = *changes ?m2*
using *c1 c2 c3 cast-sgn-same-map list.map-comp*
by *metis*
then have *changes* (*map* (λ*i*. (−1)^(*nth degree-list i*)∗(*nth signs-list i*)) [*0*..<
length degree-list]) =
changes-poly-neg-inf (*eval-mpoly-poly-list val sturm-seq*)
unfolding *changes-poly-neg-inf-def sgn-neg-inf-def*
using *changes-map-sgn-eq*
by *force*
then show *sminus degree-list signs-list* = *changes-poly-neg-inf* (*eval-mpoly-poly-list
val sturm-seq*)
by *auto*
qed
have *splus*: *changes signs-list* = *changes-poly-pos-inf ?eval-ss*
proof −

have *eq1*: *map-mpoly-sign* (*lead-coeffs sturm-seq*) *l* =
map (λ*x*. *sign-rat* (*eval-mpoly val x*)) (*lead-coeffs sturm-seq*)
using *l-prop key*
by *auto*
have ∀ *i* < *length sturm-seq*. ((*sign-rat* (*eval-mpoly val* (*nth* (*lead-coeffs sturm-seq*)
i))) =
sign-rat (*sgn-pos-inf* (*nth* (*eval-mpoly-poly-list val sturm-seq*) *i*)))
proof *clarsimp*
fix *i*
assume *i* < *length sturm-seq*
have *s1*: *eval-mpoly val* (*map Polynomial.lead-coeff sturm-seq* ! *i*) = *eval-mpoly
val* (*Polynomial.lead-coeff* (*sturm-seq* ! *i*))
by (*simp add*: ‹*i* < *length sturm-seq*›)
have *s2*: *Polynomial.lead-coeff* (*map* (*eval-mpoly-poly val*) *sturm-seq* ! *i*) =
Polynomial.lead-coeff (*eval-mpoly-poly val* (*sturm-seq* ! *i*))
using ‹*i* < *length sturm-seq*› **by** *force*
let *?ssi* = (*sturm-seq* ! *i*)
have *s3*: *eval-mpoly val* (*Polynomial.lead-coeff ?ssi*) = *Polynomial.lead-coeff*
(*eval-mpoly-poly val ?ssi*)
using *eval-mpoly-commutes-helper*[*of assumps val sturm-seq*] *inset val-sat*
using ‹*i* < *length sturm-seq*› **by** *blast*
have *sign-rat* (*eval-mpoly val* (*map Polynomial.lead-coeff sturm-seq* ! *i*)) =
sign-rat (*sgn* (*Polynomial.lead-coeff* (*eval-mpoly-poly-list val sturm-seq* ! *i*)))
using *s1 s2 s3*
using *eval-mpoly-poly-list-def*
by (*simp add*: *sign-rat-def*)
then show *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff* (*sturm-seq* ! *i*)))
= *sign-rat* (*sgn-pos-inf* (*eval-mpoly-poly-list val sturm-seq* ! *i*))

unfolding *sgn-pos-inf-def*
by (*simp add*: *s1*)
qed
then have *eq2*: *map* (λ*x*. *sign-rat* (*eval-mpoly val x*)) (*lead-coeffs sturm-seq*)
=
(*map* (*sign-rat* ∘ *sgn-pos-inf*) (*eval-mpoly-poly-list val sturm-seq*))
by (*smt* (*verit*, *ccfv-threshold*) *comp-eq-dest-lhs eval-mpoly-poly-def eval-mpoly-poly-list-def key l2 length-map list.map-comp nth-map nth-map-conv same-len*)
have *map-mpoly-sign* (*lead-coeffs sturm-seq*) *l* =
(*map* (*sign-rat* ∘ *sgn-pos-inf*) (*eval-mpoly-poly-list val sturm-seq*))
using *eq1 eq2* **by** *auto*
then have *changes*
(*map* (*Sturm-Tarski.sign* ∘
eval-mpoly l)
(*lead-coeffs sturm-seq*)) =
changes
(*map* (λ*p*. *sgn* (*Polynomial.lead-coeff p*))
(*eval-mpoly-poly-list val sturm-seq*))
unfolding *changes-poly-pos-inf-def sign-rat-def map-mpoly-sign-def*
sgn-pos-inf-def
using *changes-map-sign-of-int-eq list.map-comp*
by (*metis* (*no-types*, *lifting*) *changes-map-sign-eq comp-apply nth-map-conv*)
then have *changes* (*map-mpoly-sign* (*lead-coeffs sturm-seq*) *l*) =
changes-poly-pos-inf (*eval-mpoly-poly-list val sturm-seq*)
by (*metis* (*no-types*, *lifting*) *changes-map-sign-eq changes-map-sign-of-int-eq changes-poly-pos-inf-def list.map-comp map-eq-conv map-mpoly-sign-def sgn-pos-inf-def*)
then show *?thesis* **using** *l-prop* **unfolding** *map-mpoly-sign-def* **by** *auto*
qed
show *?thesis* **using** *sminus splus* **unfolding** *changes-R-smods-multiv-def changes-R-smods-multiv-val-def*
by (*metis*)
qed

lemma *changes-R-smods-multiv-connect*:
assumes *inset*: (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv p q acc*)
assumes *degree-list*: *degree-list* = *degrees sturm-seq*

assumes *val-sat*: ∀ *p n*. ((*p*,*n*) ∈ *set assumps* ⟶ *satisfies-evaluation val p n*)

assumes *key*: *signs-list* = *map* (λ*x*. *sign-rat* (*eval-mpoly val x*)) (*lead-coeffs sturm-seq*)
shows *changes-R-smods-multiv signs-list degree-list* = *changes-R-smods-multiv-val sturm-seq val*
proof −
have *l1*: *length signs-list* = *length sturm-seq*
using *key* **by** *auto*
then have ((*map* ((λ*x*. *sign-rat* (*eval-mpoly val x*)) ∘ *Polynomial.lead-coeff*) *sturm-seq*)::*rat list*)
∈ (((λ*x*. *map* (*sign-rat* ∘ *eval-mpoly x* ∘ *Polynomial.lead-coeff*) *sturm-seq*) ‘

{*ls*. *length ls* = *length val*})::*rat list set*)
by *auto*
then have *signs-list* ∈ *mpoly-consistent-sign-vectors* (*lead-coeffs sturm-seq*) (*all-lists* (*length val*))
using *key*
unfolding *mpoly-consistent-sign-vectors-def map-mpoly-sign-def*
by (*smt* (*verit*) *all-lists-def comp-apply image-eqI map-eq-conv mem-Collect-eq sign-rat-def*)
then show *?thesis* **using** *assms changes-R-smods-multiv-connect-aux*
by *auto*
qed

lemma *changes-R-smods-multiv-val-univariate*:
assumes (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv p q acc*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
shows *changes-R-smods-multiv-val sturm-seq val* = *changes-R-smods* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*)
using *matches-ss* **unfolding** *changes-R-smods-def changes-R-smods-multiv-val-def*
using *assms changes-poly-neg-inf-def changes-poly-pos-inf-def eval-mpoly-poly-list-def spmods-smods-sgn-map-eq*(*2*) *spmods-smods-sgn-map-eq*(*3*)
spmods-multiv-sound
by *metis*

lemma *changes-R-smods-multiv-signs-list-connect*:
assumes *len-same*: *length signs-list* = *length degree-list*
assumes *key*: ((*map sign-rat signs-list*)::*rat list*) = (*signs-list-var*::*rat list*)
shows *changes-R-smods-multiv signs-list degree-list* = *changes-R-smods-multiv signs-list-var degree-list*
proof −
have *changes-same*: *changes signs-list* = *changes signs-list-var*
using *key*
using *changes-map-sign-of-int-eq map-eq-conv*
unfolding *sign-rat-def*
by (*metis* (*mono-tags*, *lifting*) *comp-apply*)
let *?ell1* = (*map* (λ*i*. (−*1*)^(*nth degree-list i*)∗(*nth signs-list i*)) [*0*..< *length degree-list*])
let *?ell2* = (*map* (λ*i*. (−*1*)^(*nth degree-list i*)∗(*nth signs-list-var i*)) [*0*..< *length degree-list*])
have ⋀*x*. *x* < *length degree-list* ⟹
sgn ((− *1*) ^ *degree-list* ! *x* ∗ *signs-list* ! *x*) = *sgn* ((− *1*) ^ *degree-list* ! *x* ∗ *map sign-rat signs-list* ! *x*)
proof −
fix *x*
assume *x* < *length degree-list*
have *h1*: *sgn* ((− *1*) ^ *degree-list* ! *x* ∗ *signs-list* ! *x*) = *sgn* ((− *1*) ^ *degree-list* ! *x*) ∗ *sgn* (*signs-list* ! *x*)
using *sgn-mult* **by** *blast*
have *h2*: *sgn* ((− *1*) ^ *degree-list* ! *x* ∗ *map sign-rat signs-list* ! *x*) = *sgn* ((−

1) ^ *degree-list* ! *x*) * *sgn* (*map sign-rat signs-list* ! *x*)
using *sgn-mult*
by *blast*
have *h3*: *sgn* (*map sign-rat signs-list* ! *x*) = *sgn* (*signs-list* ! *x*)
using *key* **unfolding** *sign-rat-def*
using ‹*x* < *length degree-list*› *len-same sgn-rat-def* **by** *fastforce*
show *sgn* ((− *1*) ^ *degree-list* ! *x* * *signs-list* ! *x*) = *sgn* ((− *1*) ^ *degree-list* ! *x* * *map sign-rat signs-list* ! *x*)
using *h1 h2 h3*
by *metis*
qed
then have *map sgn ?ell1* = *map sgn ?ell2*
using *key*
by *auto*
then have *changes ?ell1* = *changes ?ell2*
using *changes-map-sgn-eq*
by (*metis* (*no-types*, *lifting*))
then show *?thesis*
using *changes-R-smods-multiv-def changes-same sminus.simps* **by** *presburger*
qed

lemma *changes-R-smods-multiv-univariate*:
assumes (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv p q acc*)
assumes *degree-list*: *degree-list* = *degrees sturm-seq*

assumes *val-sat*: ∀ *p n*. ((*p*,*n*) ∈ *set assumps* ⟶ *satisfies-evaluation val p n*)

assumes *key*: *map* (*sign-rat*::*rat*⇒*rat*) *signs-list* = *map* (λ*x*. *sign-rat* (*eval-mpoly val x*)) (*lead-coeffs sturm-seq*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
shows *changes-R-smods-multiv signs-list degree-list* = *changes-R-smods* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*)
proof −
have *same-len*: *length signs-list* = *length degree-list*
using *degree-list key*
by (*metis length-map*)
from *changes-R-smods-multiv-signs-list-connect*[*OF same-len key*]
have *h2*:
changes-R-smods-multiv signs-list degree-list =
changes-R-smods-multiv ((*map* (λ*x*. *sign-rat* (*eval-mpoly val x*)) (*lead-coeffs sturm-seq*))) *degree-list*
by *auto*
have *h1*: *changes-R-smods-multiv* (*map* (λ*x*. *sign-rat* (*eval-mpoly val x*)) (*lead-coeffs sturm-seq*)) *degree-list* = *changes-R-smods* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val q*)
using *changes-R-smods-multiv-connect changes-R-smods-multiv-val-univariate assms* **by** *auto*
then show *?thesis* **using** *h1 h2* **by** *auto*
qed

theorem *pderiv-commutes*:
fixes *p*:: *real mpoly Polynomial.poly*
fixes *val*:: *real list*
shows *pderiv* (*eval-mpoly-poly val p*) = (*eval-mpoly-poly val* (*pderiv p*))
by (*simp add*: *eval-mpoly-map-poly-idom-hom.base.map-poly-pderiv eval-mpoly-poly-def*)

theorem *sturm-R-multiv-comm*:
shows *card* {*x*. *Polynomial.poly* (*eval-mpoly-poly val p*) *x=0*} = *changes-R-smods* (*eval-mpoly-poly val p*) ((*eval-mpoly-poly val* (*pderiv p*)))
using *pderiv-commutes Sturm-Tarski.sturm-R*
by *auto*

theorem *sturm-R-multiv2*:
assumes *q* = *pderiv p*
assumes (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv p q acc*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
shows *card* {*x*. *Polynomial.poly* (*eval-mpoly-poly val p*) *x=0*} = *changes-R-smods-multiv-val sturm-seq val*
using *changes-R-smods-multiv-val-univariate Sturm-Tarski.sturm-R sturm-R-multiv-comm*
using *assms*(*1*) *assms*(*2*) *assms*(*3*)
by *force*

theorem *restate-tarski-multiv*:
fixes *p*:: *real mpoly Polynomial.poly*
fixes *q*:: *real mpoly Polynomial.poly*
assumes (*eval-mpoly-poly val p*) ≠ *0*
assumes (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv p* ((*pderiv p*)∗*q*) *acc*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
shows *changes-R-smods-multiv-val sturm-seq val* =
int (*card* {*x*. *Polynomial.poly* (*eval-mpoly-poly val p*) *x=0* ∧ *Polynomial.poly* (*eval-mpoly-poly val q*) *x>0*})
− *int*(*card* {*x*. *Polynomial.poly* (*eval-mpoly-poly val p*) *x=0* ∧ *Polynomial.poly* (*eval-mpoly-poly val q*) *x<0*})
proof −
have *0*: *changes-R-smods-multiv-val sturm-seq val* = *changes-R-smods* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val* ((*pderiv p*)∗*q*))
using *changes-R-smods-multiv-val-univariate assms*
by *blast*
let *?p* = (*eval-mpoly-poly val p*)::*real Polynomial.poly*
let *?q* = (*eval-mpoly-poly val q*)::*real Polynomial.poly*
have *h1*: *taq* {*x*. *poly ?p x=0*} *?q* = *changes-R-smods ?p* (*pderiv ?p* ∗ *?q*)
using *sturm-tarski-R*[*symmetric*] **by** *auto*
have *pd-comm*: *pderiv* (*eval-mpoly-poly val p*) ∗ *eval-mpoly-poly val q* = *eval-mpoly-poly val* (*pderiv p* ∗ *q*)
using *eval-mpoly-poly-comm-ring-hom.hom-mult pderiv-commutes* **by** *auto*
let *?all* = {*x*. *Polynomial.poly ?p x=0*}
let *?lt* = {*x*. *Polynomial.poly ?p x=0* ∧ *Polynomial.poly ?q x* < *0*}

let *?gt* = {*x*. *Polynomial.poly ?p x=0* ∧ *Polynomial.poly ?q x* > *0*}
let *?eq* = {*x*. *Polynomial.poly ?p x=0* ∧ *Polynomial.poly ?q x* = *0*}
have *cardlt*: (∑ *x* | *poly* (*eval-mpoly-poly val p*) *x* = *0* ∧
poly (*eval-mpoly-poly val q*) *x* < *0*.
if 0 < *poly* (*eval-mpoly-poly val q*) *x then 1*
else if poly (*eval-mpoly-poly val q*) *x* = *0 then 0*
else − *1*) = −*int* (*card ?lt*)
by *auto*
have *cardgt*: (∑ *x* | *poly* (*eval-mpoly-poly val p*) *x* = *0* ∧
0 < *poly* (*eval-mpoly-poly val q*) *x*.
if 0 < *poly* (*eval-mpoly-poly val q*) *x then 1*
else if poly (*eval-mpoly-poly val q*) *x* = *0 then 0*
else − *1*) = *int* (*card ?gt*)
by *auto*
have *empty*: {*x*. *poly* (*eval-mpoly-poly val p*) *x* = *0* ∧
poly (*eval-mpoly-poly val q*) *x* < *0*} ∩
{*x*. *poly* (*eval-mpoly-poly val p*) *x* = *0* ∧
0 < *poly* (*eval-mpoly-poly val q*) *x*} = {}
by *auto*
then have *cardzer*: (∑ *x*∈{*x*. *poly* (*eval-mpoly-poly val p*) *x* = *0* ∧
poly (*eval-mpoly-poly val q*) *x* < *0*} ∩
{*x*. *poly* (*eval-mpoly-poly val p*) *x* = *0* ∧
0 < *poly* (*eval-mpoly-poly val q*) *x*}.
if 0 < *poly* (*eval-mpoly-poly val q*) *x then 1*
else if poly (*eval-mpoly-poly val q*) *x* = *0 then 0*
else − *1*) = *0* **by** *auto*
have *eq*: *?all* = *?lt* ∪ *?gt* ∪ *?eq* **by** *force*
from *poly-roots-finite*[*OF assms*(*1*)] **have** *fin*: *finite ?all* **.**
have (∑ *x* | *poly ?p x* = *0*. *Sturm-Tarski.sign* (*poly ?q x*)) = *int* (*card ?gt*) − *int* (*card ?lt*)
unfolding *eq Sturm-Tarski.sign-def*
apply (*subst sum-Un*)
apply (*auto simp add*:*fin*)
apply (*subst sum-Un*)
apply (*simp add*: *fin*)
apply (*simp add*: *fin*)
using *cardzer cardlt cardgt empty*
by *auto*
then have *changes-R-smods* (*eval-mpoly-poly val p*) (*eval-mpoly-poly val* ((*pderiv p*)∗*q*)) = *int* (*card ?gt*) − *int* (*card ?lt*)
using *h1 taq-def pd-comm*
by *metis*
then have *changes-R-smods-multiv-val sturm-seq val* = *int* (*card ?gt*) − *int* (*card ?lt*)
using *0* **by** *auto*
then show *?thesis*
by *presburger*
qed

lemma *sminus-map-sign*:
assumes *same-len*: *length signs-list* = *length degree-list*
shows *sminus degree-list signs-list* =
sminus degree-list (*map sign-rat signs-list*)
proof −
let *?xs* = (*map* (λ*i*. (− *1*) ^ *degree-list* ! *i* ∗ *signs-list* ! *i*) [*0*..<*length degree-list*])
have *changes-same*: *changes ?xs* = *changes* (*map sign-rat ?xs*)
using *changes-map-sign-eq*[*of ?xs*]
unfolding *sign-rat-def*
by (*smt* (*verit*, *best*) *Sturm-Tarski.sign-def changes-map-sign-of-int-eq map-eq-conv o-apply*)
have (*map* (λ*i*. (−*1*)^(*nth degree-list i*)∗(*nth* (*map sign-rat signs-list*) *i*)) [*0*..<
length degree-list])
= (*map sign-rat ?xs*)
proof *clarsimp*
fix *x*
assume *x* < *length degree-list*
then have *x* < *length signs-list*
using *same-len*
by *auto*
then have *p2*: *map sign-rat signs-list* ! *x* =
sign-rat (*signs-list* ! *x*)
using *nth-map* **by** *blast*
have *p1*: (− *1*) ^ *degree-list* ! *x* = (*1*::*int*) ∨ (− *1*) ^ *degree-list* ! *x* = (−*1*::*int*)
using *neg-one-even-power neg-one-odd-power* **by** *blast*
show (− *1*) ^ *degree-list* ! *x* ∗ *map sign-rat signs-list* ! *x* =
(*sign-rat* ((− *1*) ^ *degree-list* ! *x* ∗ *signs-list* ! *x*))
using *p1 p2*
by (*metis* (*no-types*, *opaque-lifting*) *mult-1 mult-minus-left neg-one-even-power neg-one-odd-power of-int-minus sign-rat-def sign-uminus*)
qed
then have *changes* (*map sign-rat ?xs*)
= *changes* (*map* (λ*i*. (−*1*)^(*nth degree-list i*)∗(*nth* (*map sign-rat signs-list*) *i*))
[*0*..< *length degree-list*])
unfolding *sign-rat-def*
by *presburger*
then have *changes* (*map* (λ*i*. (−*1*)^(*nth degree-list i*)∗(*nth signs-list i*)) [*0*..<
length degree-list])
= *changes* (*map* (λ*i*. (−*1*)^(*nth degree-list i*)∗(*nth* (*map sign-rat signs-list*) *i*))
[*0*..< *length degree-list*])
using *changes-same*
by (*metis* (*no-types*, *lifting*))
then show *?thesis* **by** *auto*
qed

lemma *changes-R-smods-multiv-map-sign*:
assumes *length signs-list* = *length degree-list*
shows *changes-R-smods-multiv signs-list degree-list* =
changes-R-smods-multiv (*map sign-rat signs-list*) *degree-list*

using *assms sminus-map-sign*
unfolding *changes-R-smods-multiv-def*
using *changes-R-smods-multiv-def changes-R-smods-multiv-signs-list-connect* **by** *presburger*

lemma *construct-NofI-single-M-univariate-superset*:
assumes *new-p*: *new-p* = *sum-list* (*map* (λ*x*. *x*^2) (*p* # *I1*))
assumes *new-q*: *new-q* = ((*pderiv new-p*)∗(*prod-list I2*))
assumes *seq-in*: (*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv new-p new-q acc*)
assumes *superset*: *set assumps* ⊆ *set assumps-superset*
assumes *good-val*: ⋀*p n*. (*p*,*n*) ∈ *set assumps-superset* ⟹ *satisfies-evaluation val p n*
shows *construct-NofI-single-M* (*assumps-superset*, *sturm-seq*) =
(*assumps-superset*, *construct-NofI-R* (*eval-mpoly-poly val p*) (*eval-mpoly-poly-list val I1*) (*eval-mpoly-poly-list val I2*))
proof −
let *?other-p* = *sum-list* (*map power2* (*eval-mpoly-poly val p* # *eval-mpoly-poly-list val I1*))
have *eval-mpoly-poly val* (*sum-list* (*map power2 I1*)) = *sum-list* (*map power2* (*eval-mpoly-poly-list val I1*))
proof (*induct I1*)
case *Nil*
then show *?case*
by (*simp add*: *eval-mpoly-poly-list-def*)
next
case (*Cons a I1*)
then show *?case*
by (*simp add*: *eval-mpoly-poly-comm-ring-hom.hom-add eval-mpoly-poly-comm-ring-hom.hom-power eval-mpoly-poly-list-def*)
qed
then have *eval1*: *?other-p* = *eval-mpoly-poly val new-p*
using *new-p eval-mpoly-poly-comm-ring-hom.hom-add eval-mpoly-poly-comm-ring-hom.hom-power*
by *auto*
then have *eval2*: (*pderiv ?other-p* ∗ *prod-list* (*eval-mpoly-poly-list val I2*)) = *eval-mpoly-poly val new-q*
using *new-q eval-mpoly-poly-comm-ring-hom.hom-mult*
by (*simp add*: *eval-mpoly-poly-list-def pderiv-commutes*)
let *?new-signs* = (*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *i*) ∘
Polynomial.lead-coeff) *sturm-seq*)

have *lookup-some*: ⋀*ss-poly*.
ss-poly ∈ *set sturm-seq* ⟹ ∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*
proof −
fix *ss-poly*
assume *ss-poly* ∈ *set sturm-seq*
then show ∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*

using *seq-in spmods-multiv-sturm-lc*[*of assumps sturm-seq new-p new-q acc ss-poly*]
inset-means-lookup-assump-some
by *metis*
qed
have $\bigwedge$*ss-poly*. *ss-poly* $\in$ *set sturm-seq* $\Longrightarrow$
($\exists$ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i* $\wedge$
sign-rat i = *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff ss-poly*)))
proof −
fix *ss-poly*
assume *ss-poly* $\in$ *set sturm-seq*
then have $\exists$ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*
using *lookup-some* **by** *auto*
then obtain *i* **where** *i-prop*: *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*
by *auto*
then have ((*Polynomial.lead-coeff ss-poly*), *i*) $\in$ *set assumps*
using *lookup-assump-means-inset*[*of* (*Polynomial.lead-coeff ss-poly*) *assumps*]
by (*simp add*: *lookup-assum-aux-mem*)
then have (*sign-rat* (*i*)) = *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff ss-poly*))
using *good-val*[*of* (*Polynomial.lead-coeff ss-poly*) *i*] **unfolding** *satisfies-evaluation-def*
by (*metis of-int-hom.injectivity sign-rat-def subsetD superset*)
then show ($\exists$ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i* $\wedge$
sign-rat i = *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff ss-poly*)))
using *i-prop* **by** *auto*
qed
then have *help1*: $\bigwedge$*ss-poly*. *ss-poly* $\in$ *set sturm-seq* $\Longrightarrow$
($\exists$ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps-superset* = *Some i*)
using *superset sign-rat-def good-val inset-means-lookup-assump-some lookup-assum-aux-mem satisfies-evaluation-def subset-code*(*1*)
by (*smt* (*verit*, *ccfv-SIG*))
then have *help2*: $\bigwedge$*ss-poly*. $\bigwedge$ *i*. (*ss-poly* $\in$ *set sturm-seq* $\wedge$ *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps-superset* = *Some i*) $\Longrightarrow$ *sign-rat i* = *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff ss-poly*))
proof −
fix *ss-poly*
fix *i*
assume (*ss-poly* $\in$ *set sturm-seq* $\wedge$ *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps-superset* = *Some i*)
then show *sign-rat i* = *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff ss-poly*))
using *superset sign-rat-def good-val lookup-assum-aux-mem satisfies-evaluation-def*
by (*metis of-int-hom.eq-iff*)
qed
then have *all-ex-i*: $\bigwedge$*ss-poly*. *ss-poly* $\in$ *set sturm-seq* $\Longrightarrow$
($\exists$ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps-superset* =

Some i ∧
sign-rat i = sign-rat (*eval-mpoly val* (*Polynomial.lead-coeff ss-poly*)))
using *help1 help2*
by *blast*
then have *helper*: (*map* ((λ*lc. case lookup-assump-aux lc assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq) = *map* (λ*x. sign-rat* (*eval-mpoly val x*)) (*lead-coeffs sturm-seq*)
by *force*
then have *rel1*: (*changes-R-smods-multiv*
(*map* ((λ*lc. case lookup-assump-aux lc assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*)) = *changes-R-smods-multiv-val sturm-seq val*
using *helper changes-R-smods-multiv-connect*[*of assumps sturm-seq new-p new-q acc degrees sturm-seq val ?new-signs*]
using *assms*
by (*simp add*: *changes-R-smods-multiv-connect subset-code*(*1*))
have *rel2*: *changes-R-smods-multiv-val sturm-seq val* =
changes-R-smods (*eval-mpoly-poly val new-p*) (*eval-mpoly-poly val new-q*)
using *assms changes-R-smods-multiv-val-univariate*[*of assumps sturm-seq new-p new-q acc val*]
eval1 eval2
by *blast*
have *c1*: (*changes-R-smods-multiv*
(*map* ((λ*lc. case lookup-assump-aux lc assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*)) =
(*changes-R-smods ?other-p* (*pderiv ?other-p* ∗ *prod-list* (*eval-mpoly-poly-list val I2*)))
using *rel1 rel2*
using *eval1 eval2*
by *presburger*
have ⋀*ss-poly. ss-poly* ∈ *set sturm-seq* ⟹
(*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) =
sign-rat (*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *i*)
proof −
fix *ss-poly*
assume *ss-poly* ∈ *set sturm-seq*
then have ∃ *i. lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps-superset* = *Some i*
using *lookup-some superset*
using *all-ex-i* **by** *blast*
then obtain *i* **where** *i-prop*: *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*)

assumps-superset = *Some i*
by *auto*
then have *eq1*: (*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) = *sign-rat i*
by *auto*
have *eq2*: *sign-rat* (*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *i*) = *sign-rat i*
using *i-prop* **by** *auto*
then show (*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*)
assumps-superset of
None ⇒ *1000* | *Some i* ⇒ *sign-rat i*) =
sign-rat
(*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*)
assumps-superset of
None ⇒ *1000* | *Some i* ⇒ *i*)
using *eq1 eq2*
by *fastforce*
qed
then have (*map* ((λ*lc*. *case lookup-assump-aux lc assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
= (*map sign-rat* (*map* ((λ*lc*. *case lookup-assump-aux lc assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *i*) ∘
Polynomial.lead-coeff)
sturm-seq))
by *auto*
then have (*changes-R-smods-multiv*
(*map* ((λ*lc*. *case lookup-assump-aux lc assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*))
= (*changes-R-smods-multiv*
(*map sign-rat* (*map* ((λ*lc*. *case lookup-assump-aux lc assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *i*) ∘
Polynomial.lead-coeff)
sturm-seq))
(*degrees sturm-seq*))
by (*smt* (*verit*, *ccfv-threshold*))
then have (*changes-R-smods-multiv*
(*map* ((λ*lc*. *case lookup-assump-aux lc assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*)) =
(*changes-R-smods-multiv*
(*map* ((λ*lc*. *case lookup-assump-aux lc assumps-superset of None* ⇒ *1000* | *Some i* ⇒ *i*) ∘

```
        Polynomial.lead-coeff)
      sturm-seq)
    (degrees sturm-seq))
  using changes-R-smods-multiv-map-sign
  by (metis (no-types, lifting) length-map)
 then have c2: (changes-R-smods-multiv
    (map ((λlc. case lookup-assump-aux lc assumps-superset of None ⇒ 1000 |
Some i ⇒ i) ∘
        Polynomial.lead-coeff)
      sturm-seq)
    (degrees sturm-seq)) =
  (changes-R-smods ?other-p (pderiv ?other-p ∗ prod-list (eval-mpoly-poly-list val
I2)))
  using c1
  by presburger
 show ?thesis using c2
  unfolding construct-NofI-R-def
  apply (simp) unfolding construct-NofI-R-def
  by (metis)
qed


lemma construct-NofI-single-M-univariate:
 assumes new-p: new-p = sum-list (map (λx. x^2) (p # I1))
 assumes new-q: new-q = ((pderiv new-p)∗(prod-list I2))
 assumes seq-in: (assumps, sturm-seq) ∈ set (spmods-multiv new-p new-q acc)
 assumes good-val: ⋀p n. (p,n) ∈ set assumps ⟹ satisfies-evaluation val p n
 shows construct-NofI-single-M (assumps, sturm-seq) =
  (assumps, construct-NofI-R (eval-mpoly-poly val p) (eval-mpoly-poly-list val I1)
(eval-mpoly-poly-list val I2))
proof −
 let ?other-p = sum-list (map power2 (eval-mpoly-poly val p # eval-mpoly-poly-list
val I1))
  have eval-mpoly-poly val (sum-list (map power2 I1)) = sum-list (map power2
(eval-mpoly-poly-list val I1))
 proof (induct I1)
  case Nil
  then show ?case
   by (simp add: eval-mpoly-poly-list-def)
 next
  case (Cons a I1)
  then show ?case
   by (simp add: eval-mpoly-poly-comm-ring-hom.hom-add eval-mpoly-poly-comm-ring-hom.hom-power
eval-mpoly-poly-list-def)
 qed
 then have eval1: ?other-p = eval-mpoly-poly val new-p
  using new-p eval-mpoly-poly-comm-ring-hom.hom-add eval-mpoly-poly-comm-ring-hom.hom-power
   by auto
  then have eval2: (pderiv ?other-p ∗ prod-list (eval-mpoly-poly-list val I2)) =
```

eval-mpoly-poly val new-q
using *new-q eval-mpoly-poly-comm-ring-hom.hom-mult*
by (*simp add*: *eval-mpoly-poly-list-def pderiv-commutes*)
let *?new-signs* = (*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000*
| *Some i* ⇒ *i*) ∘
Polynomial.lead-coeff) *sturm-seq*)

have *lookup-some*: ⋀*ss-poly*.
ss-poly ∈ *set sturm-seq* ⟹ ∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*
proof −
fix *ss-poly*
assume *ss-poly* ∈ *set sturm-seq*
then show ∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*
using *seq-in spmods-multiv-sturm-lc*[*of assumps sturm-seq new-p new-q acc ss-poly*]
inset-means-lookup-assump-some
by *metis*
qed
have ⋀*ss-poly*. *ss-poly* ∈ *set sturm-seq* ⟹
(∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i* ∧
sign-rat i = *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff ss-poly*)))
proof −
fix *ss-poly*
assume *ss-poly* ∈ *set sturm-seq*
then have ∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*
using *lookup-some* **by** *auto*
then obtain *i* **where** *i-prop*: *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*
by *auto*
then have ((*Polynomial.lead-coeff ss-poly*), *i*) ∈ *set assumps*
using *lookup-assump-means-inset*[*of* (*Polynomial.lead-coeff ss-poly*) *assumps*]
by (*simp add*: *lookup-assum-aux-mem*)
then have (*sign-rat* (*i*)) = *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff ss-poly*))
using *good-val*[*of* (*Polynomial.lead-coeff ss-poly*) *i*] **unfolding** *satisfies-evaluation-def*
by (*metis of-int-hom.injectivity sign-rat-def*)
then show (∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i* ∧
sign-rat i = *sign-rat* (*eval-mpoly val* (*Polynomial.lead-coeff ss-poly*)))
using *i-prop* **by** *auto*
qed
then have (*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq) = *map* (λ*x*. *sign-rat* (*eval-mpoly val x*)) (*lead-coeffs sturm-seq*)
by *force*

then have *rel1*: (*changes-R-smods-multiv*
(*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*)) = *changes-R-smods-multiv-val sturm-seq val*
using *changes-R-smods-multiv-connect*[*of assumps sturm-seq new-p new-q acc degrees sturm-seq val ?new-signs*]
using *assms*(*3*) *assms*(*4*)
using *changes-R-smods-multiv-connect* **by** *blast*
have *rel2*: *changes-R-smods-multiv-val sturm-seq val* =
changes-R-smods (*eval-mpoly-poly val new-p*) (*eval-mpoly-poly val new-q*)
using *assms changes-R-smods-multiv-val-univariate*[*of assumps sturm-seq new-p new-q acc val*]
eval1 eval2
by *blast*
have *c1*: (*changes-R-smods-multiv*
(*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*)) =
(*changes-R-smods ?other-p* (*pderiv ?other-p* ∗ *prod-list* (*eval-mpoly-poly-list val I2*)))
using *rel1 rel2*
using *eval1 eval2*
by *presburger*
have ⋀*ss-poly*. *ss-poly* ∈ *set sturm-seq* ⟹
(*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) =
sign-rat (*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps of None* ⇒ *1000* | *Some i* ⇒ *i*)
proof −
fix *ss-poly*
assume *ss-poly* ∈ *set sturm-seq*
then have ∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*
using *lookup-some* **by** *auto*
then obtain *i* **where** *i-prop*: *lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps* = *Some i*
by *auto*
then have *eq1*: (*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) = *sign-rat i*
by *auto*
have *eq2*: *sign-rat* (*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps of None* ⇒ *1000* | *Some i* ⇒ *i*) = *sign-rat i*
using *i-prop* **by** *auto*
then show (*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) =

sign-rat (*case lookup-assump-aux* (*Polynomial.lead-coeff ss-poly*) *assumps of None* ⇒ *1000* | *Some i* ⇒ *i*)
using *eq1 eq2*
by *metis*
qed
then have (*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
= (*map sign-rat* (*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *i*) ∘
Polynomial.lead-coeff)
sturm-seq))
by *auto*
then have *changes-1*: (*changes-R-smods-multiv*
(*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*))
= (*changes-R-smods-multiv*
(*map sign-rat* (*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *i*) ∘
Polynomial.lead-coeff)
sturm-seq))
(*degrees sturm-seq*))
by (*smt* (*verit*, *ccfv-threshold*))
then have *changes2*: (*changes-R-smods-multiv*
(*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *sign-rat i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*)) =
(*changes-R-smods-multiv*
(*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*))
using *changes-R-smods-multiv-map-sign*
by (*metis* (*no-types*, *lifting*) *length-map*)
then have (*changes-R-smods-multiv*
(*map* ((λ*lc*. *case lookup-assump-aux lc assumps of None* ⇒ *1000* | *Some i* ⇒ *i*) ∘
Polynomial.lead-coeff)
sturm-seq)
(*degrees sturm-seq*)) =
(*changes-R-smods ?other-p* (*pderiv ?other-p* ∗ *prod-list* (*eval-mpoly-poly-list val I2*)))

using *c1*
by *presburger*
then show *?thesis*
unfolding *construct-NofI-R-def* **using** *c1 changes2*
by (*smt* (*verit*, *ccfv-SIG*) *construct-NofI-R-def construct-NofI-single-M-univariate-superset dual-order.refl good-val new-p new-q seq-in*)

qed

lemma *construct-NofI-M-univariate-tarski-query*:
assumes *inset*: (*assumps*, *tarski-query*) ∈ *set* (*construct-NofI-M p acc I1 I2*)
assumes *val*: ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
shows *tarski-query* = *construct-NofI-R* (*eval-mpoly-poly val p*) (*eval-mpoly-poly-list val I1*) (*eval-mpoly-poly-list val I2*)
proof −
let *?ell-map* = *map construct-NofI-single-M* (*construct-NofI-R-spmods p acc I1 I2*)
let *?ell* = *construct-NofI-R-spmods p acc I1 I2*
have *same-len*: *length ?ell* = *length ?ell-map*
by *auto*
have (*assumps*, *tarski-query*) ∈ *set* (*map construct-NofI-single-M* (*construct-NofI-R-spmods p acc I1 I2*))
using *inset*
by (*metis construct-NofI-M.simps*)
then have ∃ *n* < *length ?ell-map*. *?ell-map* ! *n* = (*assumps*, *tarski-query*)
by (*metis construct-NofI-M.simps in-set-conv-nth inset length-map*)
then obtain *n* **where** *n-prop*: *n* < *length ?ell-map* ∧ *?ell-map* ! *n* = (*assumps*, *tarski-query*)
by *auto*
then have *?ell-map* ! *n* = *construct-NofI-single-M* (*?ell* ! *n*)
by *force*
then have *assumps-tq*: *construct-NofI-single-M* (*?ell* ! *n*) = (*assumps*, *tarski-query*)
using *n-prop* **by** *auto*
obtain *input-assumps ss* **where** *tuple-prop*: (*input-assumps*, *ss*) = *?ell* ! *n*
using *n-prop same-len*
by (*metis old.prod.exhaust*)
then have *atq-is*: (*assumps*, *tarski-query*) =
(*let lcs* = *lead-coeffs ss*;
sa-list = *map* (λ*lc*. *lookup-assump lc input-assumps*) *lcs*;
degrees-list = *degrees ss in*
(*input-assumps*, *rat-of-int* (*changes-R-smods-multiv sa-list degrees-list*)))
by (*metis assumps-tq construct-NofI-single-M.simps*)
then have *as-is*: *assumps* = *input-assumps*
by *auto*
have *in-spmods-multiv*: (*assumps*, *ss*) ∈ *set* ((*let new-p* = *sum-list* (*map* (λ*x*. *x*^2) (*p* # *I1*)) *in*
spmods-multiv new-p ((*pderiv new-p*)∗(*prod-list I2*))) *acc*)
using *tuple-prop*
using *as-is construct-NofI-R-spmods-def n-prop* **by** *auto*

let *?multiv-p* = *sum-list* (*map power2* (*p* # *I1*))
let *?multiv-q* = (*pderiv ?multiv-p* ∗ *prod-list I2*)
let *?univ-p* = *sum-list* (*map power2* (*eval-mpoly-poly val p* # *eval-mpoly-poly-list val I1*))
let *?univ-q* = (*pderiv ?univ-p* ∗ *prod-list* (*eval-mpoly-poly-list val I2*))
let *?signs-list* = *map* (λ*lc. lookup-assump lc assumps*) (*lead-coeffs ss*)
have *map-poly* (*eval-mpoly val*) (p^2 + *sum-list* (*map power2 I1*)) =
(*map-poly* (*eval-mpoly val*) *p*)^2 + *sum-list* (*map* (*power2* ∘ *map-poly* (*eval-mpoly val*)) *I1*)
using *eval-mpoly-map-poly-comm-ring-hom.hom-mult eval-mpoly-map-poly-comm-ring-hom.hom-sum*
proof −
have *h1*: *map-poly* (*eval-mpoly val*) (p^2 + *sum-list* (*map power2 I1*)) = (*map-poly* (*eval-mpoly val*) *p*)^2 + *map-poly* (*eval-mpoly val*) (*sum-list* (*map power2 I1*))
using *eval-mpoly-map-poly-comm-ring-hom.hom-add eval-mpoly-map-poly-comm-ring-hom.hom-power*
by *presburger*
have *map-poly* (*eval-mpoly val*) (*sum-list* (*map power2 I1*)) =
(*sum-list* (*map* (*map-poly* (*eval-mpoly val*)∘*power2*) *I1*))
using *eval-mpoly-map-poly-comm-ring-hom.hom-add*
by (*simp add*: *eval-mpoly-map-poly-comm-ring-hom.hom-sum-list*)
then have *h2*: *map-poly* (*eval-mpoly val*) (*sum-list* (*map power2 I1*)) = *sum-list* (*map* (*power2* ∘ *map-poly* (*eval-mpoly val*)) *I1*)
using *eval-mpoly-map-poly-comm-ring-hom.hom-add eval-mpoly-map-poly-comm-ring-hom.hom-power*
by (*metis* (*mono-tags*, *lifting*) *comp-apply map-eq-conv*)
then show *?thesis*
using *h1 h2* **by** *auto*
qed
then have *p-connect*: *eval-mpoly-poly val ?multiv-p* = *?univ-p*
unfolding *eval-mpoly-poly-def eval-mpoly-poly-list-def*
by *auto*
then have *eval-mpoly-poly val* (*pderiv ?multiv-p*) = *pderiv ?univ-p*
by (*metis pderiv-commutes*)
then have *q-connect*: *eval-mpoly-poly val ?multiv-q* = *?univ-q*
using *eval-mpoly-map-poly-comm-ring-hom.hom-mult*
unfolding *eval-mpoly-poly-list-def*
using *eval-mpoly-poly-comm-ring-hom.hom-mult eval-mpoly-poly-comm-ring-hom.prod-list-map-hom*
by *presburger*
have *tq-is*: *tarski-query* =
(*let lcs* = *lead-coeffs ss*;
sa-list = *map* (λ*lc. lookup-assump lc assumps*) *lcs*;
degrees-list = *degrees ss in*
rat-of-int (*changes-R-smods-multiv sa-list degrees-list*))
using *as-is atq-is* **by** *auto*
have ⋀*x*. *x* ∈ *set ss* ⟹
sign-rat
(*case lookup-assump-aux* (*Polynomial.lead-coeff x*) *assumps of None* ⇒ *1000* | *Some i* ⇒ *i*) =
sign-rat (*eval-mpoly val* (*Polynomial.lead-coeff x*))
proof −

fix x
assume $x \in$ *set ss*
then have $\exists i$. (*Polynomial.lead-coeff* x, i) $\in$ *set assumps*
using *in-spmods-multiv spmods-multiv-sturm-lc*[*of assumps ss - - acc x*]
by *meson*
then obtain i **where** *i-prop*: (*Polynomial.lead-coeff* x, i) $\in$ *set assumps*
by *auto*
then have *satisfies-evaluation val* (*Polynomial.lead-coeff* x) i
using *val*
by *auto*
then have $\bigwedge j$. (*Polynomial.lead-coeff* x, j) $\in$ *set assumps* $\Longrightarrow$ *sign-rat* i = *sign-rat* j
using *val* **unfolding** *satisfies-evaluation-def*
by (*metis of-int-hom.injectivity sign-rat-def*)
then have $\exists j$. (*case lookup-assump-aux* (*Polynomial.lead-coeff* x) *assumps of None* $\Rightarrow$ *1000* | *Some* $i \Rightarrow i$) = $j \wedge$ *sign-rat* i = *sign-rat* j
by (*smt* (*verit*, *del-insts*) *i-prop inset-means-lookup-assump-some lookup-assum-aux-mem option.case*(*2*))
then show *sign-rat*
(*case lookup-assump-aux* (*Polynomial.lead-coeff* x) *assumps of None* $\Rightarrow$ *1000* | *Some* $i \Rightarrow i$) =
sign-rat (*eval-mpoly val* (*Polynomial.lead-coeff* x))
using *i-prop val*
by (*metis of-int-hom.injectivity satisfies-evaluation-def sign-rat-def*)
qed
then have *map sign-rat* (*map* (λ*lc. lookup-assump lc assumps*) (*lead-coeffs ss*)) =
map (λx. *sign-rat* (*eval-mpoly val x*)) (*lead-coeffs ss*)
using *val* **by** *auto*
then have *changes-R-smods-multiv* (*map* (λ*lc. lookup-assump lc assumps*) (*lead-coeffs ss*)) (*degrees ss*) =
changes-R-smods (*eval-mpoly-poly val* (*sum-list* (*map power2* (*p* # *I1*))))
(*eval-mpoly-poly val* (*pderiv* (*sum-list* (*map power2* (*p* # *I1*))) $*$ *prod-list I2*))
using *changes-R-smods-multiv-univariate*[*of assumps ss ?multiv-p ?multiv-q acc degrees ss val ?signs-list*] *in-spmods-multiv val*
by (*smt* (*verit*, *ccfv-SIG*))
then show *?thesis*
unfolding *construct-NofI-R-def*
using *p-connect q-connect tq-is*
by *metis*
qed

end

theory *Renegar-Modified*

imports *BenOr-Kozen-Reif.Renegar-Decision*

begin

definition *poly-f-nocrb* :: *real poly list* ⇒ *real poly*
where
poly-f-nocrb ps =
(*if* (*check-all-const-deg ps* = *True*) *then* [:*0*, *1*:] *else*
(*pderiv* (*prod-list-var ps*)) ∗ (*prod-list-var ps*))

lemma *root-set-nocrb*:
assumes *is-not-const*: *check-all-const-deg qs* = *False*
shows {*x*. *poly* (*poly-f qs*) *x* = *0*}
= {*x*. *poly* (*poly-f-nocrb qs*) *x* = *0*} ∪ {−(*crb* (*prod-list-var qs*)), (*crb* (*prod-list-var qs*))}
proof −
have ∀ *x* ∈ {*x*. *poly* (*poly-f qs*) *x* = *0*}. *poly* (*poly-f qs*) *x* = *0* **by** *auto*
then have *all*: ∀ *x* ∈ {*x*. *poly* (*poly-f qs*) *x* = *0*}. *poly* ((*pderiv* (*prod-list-var qs*)) ∗ (*prod-list-var qs*)∗ ([:−(*crb* (*prod-list-var qs*)),*1*:]) ∗ ([:(*crb* (*prod-list-var qs*)),*1*:])) *x* = *0*
unfolding *poly-f-def* **using** *is-not-const* **by** *presburger*
have *all1*: ∀ *x* ∈ {*x*. *poly* (*poly-f qs*) *x* = *0*}.
((*poly* ((*pderiv* (*prod-list-var qs*)) ∗ (*prod-list-var qs*)) *x* = *0*)
∨ (*poly* (([:−(*crb* (*prod-list-var qs*)),*1*:]) ∗ ([:(*crb* (*prod-list-var qs*)),*1*:])) *x* = *0*))
proof *clarsimp*
fix *x*
assume *inset*: *poly* (*poly-f qs*) (*real-of-int x*) = *0*
assume *poly* (*pderiv* (*prod-list-var qs*)) (*real-of-int x*) ≠ *0*
assume *x* ∗ *x* ≠ *crb* (*prod-list-var qs*) ∗ *crb* (*prod-list-var qs*)
have *poly* ((*pderiv* (*prod-list-var qs*)) ∗ (*prod-list-var qs*)∗ ([:−(*crb* (*prod-list-var qs*)),*1*:]) ∗ ([:(*crb* (*prod-list-var qs*)),*1*:])) *x* = *0*
using *all inset* **by** *auto*
then show *poly* (*prod-list-var qs*) (*real-of-int x*) = *0* **using** *assms*
by (*smt* (*verit*, *del-insts*) ‹*poly* (*pderiv* (*prod-list-var qs*)) (*real-of-int x*) ≠ *0*› ‹*x* ∗ *x* ≠ *crb* (*prod-list-var qs*) ∗ *crb* (*prod-list-var qs*)› *mult.commute mult-eq-0-iff mult-minus-left of-int-eq-iff of-int-minus poly-mult poly-root-factor*(*3*))
qed
have ∀ *x*. (*poly* (([:−(*crb* (*prod-list-var qs*)),*1*:]) ∗ ([:(*crb* (*prod-list-var qs*)),*1*:])) *x* = *0* ⟶
(*x* = −(*crb* (*prod-list-var qs*)) ∨ *x* = (*crb* (*prod-list-var qs*))))
by (*simp add*: *square-eq-iff*)
then have ∀ *x* ∈ {*x*. *poly* (*poly-f qs*) *x* = *0*}.
((*poly* (*poly-f-nocrb qs*) *x* = *0*)
∨ (*x* = −(*crb* (*prod-list-var qs*)) ∨ *x* = (*crb* (*prod-list-var qs*))))
using *all1* **unfolding** *poly-f-nocrb-def*
by (*smt* (*verit*, *del-insts*) *all is-not-const of-int-minus poly-root-factor*(*2*))
then have *subset1*: {*x*. *poly* (*poly-f qs*) *x* = *0*}
⊆ {*x*. *poly* (*poly-f-nocrb qs*) *x* = *0*} ∪ {−(*crb* (*prod-list-var qs*)), (*crb* (*prod-list-var qs*))}
using *UnCI is-not-const mem-Collect-eq* **by** *fastforce*

have *subset2*: $\{x.\ poly\ (poly\text{-}f\text{-}nocrb\ qs)\ x = 0\} \cup \{-(crb\ (prod\text{-}list\text{-}var\ qs)), (crb\ (prod\text{-}list\text{-}var\ qs))\} \subseteq$
$\{x.\ poly\ (poly\text{-}f\ qs)\ x = 0\}$
using *Un-insert-right insert-iff is-not-const mem-Collect-eq of-int-minus poly-f-def poly-f-nocrb-def* **by** *auto*
then show *?thesis* **using** *subset1 subset2* **by** *auto*
qed

lemma *nonzcrb-helper*:
assumes *q-in*: $q \in set\ qs$
assumes *qnonz*: $q \neq 0$
assumes *lengt*: $length\ (sorted\text{-}list\text{-}of\text{-}set\ \{(x::real).\ (\exists\, q \in set(qs).\ (q \neq 0 \wedge poly\ q\ x = 0))\} :: real\ list) > 0$
shows $\neg(\exists\, x \geq (real\text{-}of\text{-}int\ (crb\ (prod\text{-}list\text{-}var\ qs))).\ poly\ q\ x = 0)$
proof *clarsimp*
fix *x*
assume *xgt*: $real\text{-}of\text{-}int\ (crb\ (prod\text{-}list\text{-}var\ qs)) \leq x$
assume *pqz*: $poly\ q\ x = 0$
let *?zer-list* = $sorted\text{-}list\text{-}of\text{-}set\ \{(x::real).\ (\exists\, q \in set(qs).\ (q \neq 0 \wedge poly\ q\ x = 0))\} :: real\ list$
have *strict-sorted-h*: $sorted\text{-}wrt\ (<)\ ?zer\text{-}list$ **using** *sorted-sorted-list-of-set strict-sorted-iff* **by** *auto*
have *finset*: $finite\ \{x.\ \exists\, q{\in}set\ qs.\ q \neq 0 \wedge poly\ q\ x = 0\}$
proof −
have $\forall\, q \in set\ qs.\ q{\neq}\ 0 \longrightarrow finite\ \{x.\ poly\ q\ x = 0\}$
using *poly-roots-finite* **by** *auto*
then show *?thesis* **by** *auto*
qed
have *all-prop*: $\forall\, x \in \{x.\ \exists\, q{\in}set\ qs.\ q \neq 0 \wedge poly\ q\ x = 0\}.\ poly\ (prod\text{-}list\text{-}var\ qs)\ x = 0$
using *q-dvd-prod-list-var-prop*
by *fastforce*
then have $poly\ (prod\text{-}list\text{-}var\ qs)\ (sorted\text{-}list\text{-}of\text{-}set\ \{x.\ \exists\, q{\in}set\ qs.\ q \neq 0 \wedge poly\ q\ x = 0\}\ !\ 0) = 0$
using *finset set-sorted-list-of-set*
by (*metis* (*no-types*, *lifting*) *lengt nth-mem*)
then have *crbgt*: $crb\ (prod\text{-}list\text{-}var\ qs) > ?zer\text{-}list\ !\ (length\ ?zer\text{-}list - 1)$ **using** *prod-list-var-nonzero crb-lem-pos*[*of prod-list-var qs ?zer-list* ! (*length ?zer-list* − *1*)]
by (*metis* (*no-types*, *lifting*) *all-prop diff-less finset lengt less-numeral-extra*(*1*) *nth-mem set-sorted-list-of-set*)
have *x-in*: $x \in \{x.\ \exists\, q{\in}set\ qs.\ q \neq 0 \wedge poly\ q\ x = 0\}$
using *pqz q-in qnonz*
by *auto*
then have $x \in set\ ?zer\text{-}list$
by (*smt* (*verit*, *best*) *finset mem-Collect-eq set-sorted-list-of-set*)
then have $x \leq ?zer\text{-}list\ !\ (length\ ?zer\text{-}list - 1)$ **using** *strict-sorted-h*
by (*meson all-prop x-in crb-lem-pos not-less prod-list-var-nonzero xgt*)
then show *False* **using** *xgt crbgt*

by *auto*
qed

lemma *root-set-nocrb-var*:
assumes *is-not-const*: *check-all-const-deg qs = False*
shows ({*x*. *poly* (*poly-f qs*) *x* = *0*}::*real set*)
= {*x*. *poly* (*poly-f-nocrb qs*) *x* = *0*} ∪ (({−(*crb* (*prod-list-var qs*)), (*crb* (*prod-list-var qs*))})::*real set*)
using *root-set-nocrb* **apply** (*auto*)
apply (*smt* (*verit*) *of-int-minus poly-f-def poly-f-nocrb-def poly-root-factor*(*2*))
apply (*simp add*: *is-not-const poly-f-def*)
using *is-not-const* **apply** *blast*
by (*metis* (*no-types*, *lifting*) *poly-f-def poly-f-nocrb-def poly-root-factor*(*2*))

lemma *nonzcrb*:
assumes *q-in*: *q* ∈ *set qs*
assumes *qnonz*: *q* ≠ *0*
shows ¬(∃ *x* ≥ (*real-of-int* (*crb* (*prod-list-var qs*))). *poly q x* = *0*)
proof −
let *?zer-list* = (*sorted-list-of-set* {(*x*::*real*). (∃ *q* ∈ *set*(*qs*). (*q* ≠ *0* ∧ *poly q x* = *0*))} :: *real list*)
have *eo*: *length ?zer-list* = *0* ∨ *length ?zer-list* > *0*
by *auto*
have *h1*: *length ?zer-list* = *0* ⟶ ¬(∃ *x* ≥ (*real-of-int* (*crb* (*prod-list-var qs*))). *poly q x* = *0*)
by (*metis crb-lem-pos dvdE linorder-not-less mult-zero-left poly-mult prod-list-var-nonzero q-dvd-prod-list-var-prop q-in qnonz*)
have *h2*: *length ?zer-list* > *0* ⟶ ¬(∃ *x* ≥ (*real-of-int* (*crb* (*prod-list-var qs*))). *poly q x* = *0*)
using *nonzcrb-helper assms*
by *blast*
show *?thesis* **using** *eo h1 h2*
by *auto*
qed

definition *sgn-pos-inf-rat-list*:: *real poly list* ⇒ *int list*
where *sgn-pos-inf-rat-list l* = *map* (λ*x*. (*Sturm-Tarski.sign* (*sgn-pos-inf x*))) *l*

definition *sgn-neg-inf-rat-list*:: *real poly list* ⇒ *int list*
where *sgn-neg-inf-rat-list l* = *map* (λ*x*. (*Sturm-Tarski.sign* (*sgn-neg-inf x*))) *l*

definition *sgn-neg-inf-rat-list2*:: *real poly list* ⇒ *rat list*
where *sgn-neg-inf-rat-list2 l* = *map* (λ*x*. ((*rat-of-int* ∘ *Sturm-Tarski.sign*) (*sgn-neg-inf x*))) *l*

definition *sgn-pos-inf-rat-list2*:: *real poly list* ⇒ *rat list*
where *sgn-pos-inf-rat-list2 l* = *map* (λ*x*. ((*rat-of-int* ∘ *Sturm-Tarski.sign*) (*sgn-pos-inf x*))) *l*

lemma *root-ub-restate*:
fixes *p*:: *real poly*
assumes *pnonz*: $p \neq 0$
fixes *z*::*real*
assumes *zgt*: $\forall x.\ poly\ p\ x{=}0 \longrightarrow x < z$
shows $x{\geq}z \Longrightarrow sgn\ (poly\ p\ x) = Sturm\text{-}Tarski.sign\ (sgn\text{-}pos\text{-}inf\ p)$
proof −
assume *xgt*: $x{\geq}z$
have *allx*: $\forall x \geq z.\ sgn\ (poly\ p\ x) = sgn\ (poly\ p\ z)$
proof *clarsimp*
fix *x*
assume *zleq*: $z \leq x$
then have *xnonz*: $sgn\ (poly\ p\ x) \neq 0$
using *zgt* **unfolding** *sgn-def* **by** *auto*
have *znonz*: $sgn\ (poly\ p\ z) \neq 0$
using *zgt* **unfolding** *sgn-def* **by** *auto*
have *Matrix-Equation-Construction.sgn* $(poly\ p\ x) \neq$ *Matrix-Equation-Construction.sgn* $(poly\ p\ z) \Longrightarrow$ *False*
proof −
assume *neq*: *Matrix-Equation-Construction.sgn* $(poly\ p\ x) \neq$ *Matrix-Equation-Construction.sgn* $(poly\ p\ z)$
then have *z-lt*: $z < x$ **using** *zleq*
using *less-eq-real-def* **by** *force*
have *h1*: $z < x \Longrightarrow$
Matrix-Equation-Construction.sgn $(poly\ p\ z) \neq 0 \Longrightarrow$
Matrix-Equation-Construction.sgn $(poly\ p\ x) \neq 0 \Longrightarrow$
$\neg\ poly\ p\ x < 0 \Longrightarrow 0 < poly\ p\ x$
using *zgt* **by** *fastforce*
have *h2*: $z < x \Longrightarrow$
Matrix-Equation-Construction.sgn $(poly\ p\ z) \neq 0 \Longrightarrow$
Matrix-Equation-Construction.sgn $(poly\ p\ x) \neq 0 \Longrightarrow$
$\neg\ poly\ p\ x < 0 \Longrightarrow poly\ p\ z < 0$
by (*metis neq sgn-def*)
have *h3*: $z < x \Longrightarrow$
Matrix-Equation-Construction.sgn $(poly\ p\ z) \neq 0 \Longrightarrow$
Matrix-Equation-Construction.sgn $(poly\ p\ x) \neq 0 \Longrightarrow$
$\neg\ 0 < poly\ p\ z \Longrightarrow 0 < poly\ p\ x$
by (*metis neq sgn-def*)
have *h4*: $z < x \Longrightarrow$
Matrix-Equation-Construction.sgn $(poly\ p\ z) \neq 0 \Longrightarrow$
Matrix-Equation-Construction.sgn $(poly\ p\ x) \neq 0 \Longrightarrow$
$\neg\ 0 < poly\ p\ z \Longrightarrow poly\ p\ z < 0$
using *h2 h3* **by** *linarith*
have $((poly\ p\ x) > 0 \wedge (poly\ p\ z) < 0) \vee ((poly\ p\ x) < 0 \wedge (poly\ p\ z) > 0)$
using *z-lt znonz xnonz h1 h2 h3 h4*
by *auto*
then have $\exists w.\ w > x \wedge w < z \wedge (poly\ p\ w = 0)$
using *poly-IVT-pos*[*of z x*] *poly-IVT-neg*[*of z x*]
by (*metis* ‹$z < x$› *not-less-iff-gr-or-eq zgt*)

```
    then show False
      using zgt
      using zleq by linarith
  qed
 then show Matrix-Equation-Construction.sgn (poly p x) = Matrix-Equation-Construction.sgn
(poly p z)
    by auto
 qed
 have (∃ ub.
       (∀ x≥ub. sgn-class.sgn (poly p x) = sgn-pos-inf p))
  using root-ub[of p] pnonz
  by meson
 then obtain ub where ub-prop: (∀ x≥ub. sgn-class.sgn (poly p x) = sgn-pos-inf
p)
  by auto
 let ?ub2 = max ub (z+1)
 have (∀ x≥?ub2. sgn-class.sgn (poly p x) = sgn-pos-inf p) ∧ (?ub2 > z)
  using ub-prop by auto
 then have h1: (Sturm-Tarski.sign(sgn-class.sgn (poly p ?ub2)::real)) = Sturm-Tarski.sign(sgn-pos-inf
p) ∧ (?ub2 > z)
  by auto
 have (Sturm-Tarski.sign(sgn-class.sgn (poly p ?ub2)::real)) = (sgn (poly p ?ub2))
  unfolding sign-def sgn-def by auto
 then have (sgn (poly p ?ub2)) = (Sturm-Tarski.sign(sgn-pos-inf p)) ∧ (?ub2 >
z)
  using h1
  by metis
 then have ∀ x≥z. sgn (poly p x) = Sturm-Tarski.sign (sgn-pos-inf p)
  using allx
  by (metis dual-order.refl max.absorb3 max.bounded-iff)
 then show ?thesis using xgt
  by auto
qed

lemma limit-pos-infinity-helper1:
 assumes q-in: q ∈ set qs
 assumes qnonz: q ≠ 0
 assumes x = (crb (prod-list-var qs))
 shows (if (poly q x > 0) then (1::int) else (if (poly q x = 0) then (0::rat) else
(−1::rat)))
  = ((Sturm-Tarski.sign (sgn-pos-inf q))::int)
 using poly-sgn-eventually-at-top[unfolded eventually-at-top-linorder]
proof −
 have (∃ ub. (∀ x. poly q x = 0 ⟶ x < ub ⟶
       (∀ x≥ub. sgn-class.sgn (poly q x) = sgn-pos-inf q)))
  using root-ub[of q] qnonz
  by meson
 then obtain ub where ub-prop: (∀ x. poly q x = 0 ⟶ x < ub ⟶
       (∀ x≥ub. sgn-class.sgn (poly q x) = sgn-pos-inf q))
```

by *auto*
show *?thesis*
proof −
have $q \in set\ qs \wedge q \neq 0$
using *q-in qnonz* **by** *blast*
then have *f1*: $\forall r.\ \neg\ real\text{-}of\text{-}int\ (crb\ (prod\text{-}list\text{-}var\ qs)) \leq r \vee 0 \neq poly\ q\ r$
by (*metis* (*no-types*) *nonzcrb*[*of q*])
have *f2*: $real\text{-}of\text{-}int\ (crb\ (prod\text{-}list\text{-}var\ qs)) \leq real\text{-}of\text{-}int\ x$
using *assms*(*3*) **by** *force*
then have *f3*: $0 \neq poly\ q\ (real\text{-}of\text{-}int\ x)$
using *f1* **by** *blast*
have *comb1*: $\bigwedge z\ x.\ [\![q \neq 0;\ \forall x.\ poly\ q\ x = 0 \longrightarrow x < z;\ z \leq x]\!] \Longrightarrow of\text{-}rat\ (Matrix\text{-}Equation\text{-}Construction.sgn\ (poly\ q\ x)) = complex\text{-}of\text{-}int\ (Sturm\text{-}Tarski.sign\ (sgn\text{-}pos\text{-}inf\ q))$
using *assms*(*2*) *root-ub-restate*[*of q*] **by** *auto*
obtain *rr* :: *real* **where**
$q \neq 0 \wedge (0 = poly\ q\ rr \longrightarrow rr < real\text{-}of\text{-}int\ (crb\ (prod\text{-}list\text{-}var\ qs))) \wedge real\text{-}of\text{-}int\ (crb\ (prod\text{-}list\text{-}var\ qs)) \leq real\text{-}of\text{-}int\ x \longrightarrow Sturm\text{-}Tarski.sign\ (sgn\text{-}pos\text{-}inf\ q) = Matrix\text{-}Equation\text{-}Construction.sgn\ (poly\ q\ (real\text{-}of\text{-}int\ x))$
by (*metis comb1*)
then have *f4*: $Sturm\text{-}Tarski.sign\ (sgn\text{-}pos\text{-}inf\ q) = Matrix\text{-}Equation\text{-}Construction.sgn\ (poly\ q\ (real\text{-}of\text{-}int\ x))$
using *f2 f1 linorder-not-less qnonz* **by** *blast*
have $Matrix\text{-}Equation\text{-}Construction.sgn\ (poly\ q\ (real\text{-}of\text{-}int\ x)) = (if\ 0 < poly\ q\ (real\text{-}of\text{-}int\ x)\ then\ 1\ else\ if\ poly\ q\ (real\text{-}of\text{-}int\ x) < 0\ then - 1\ else\ 0) \wedge (if\ 0 < poly\ q\ (real\text{-}of\text{-}int\ x)\ then\ (1::rat) = (if\ 0 < poly\ q\ (real\text{-}of\text{-}int\ x)\ then\ 1\ else\ if\ poly\ q\ (real\text{-}of\text{-}int\ x) < 0\ then - 1\ else\ 0)\ else\ (if\ 0 < poly\ q\ (real\text{-}of\text{-}int\ x)\ then\ 1::rat\ else\ if\ poly\ q\ (real\text{-}of\text{-}int\ x) < 0\ then - 1\ else\ 0) = (if\ poly\ q\ (real\text{-}of\text{-}int\ x) < 0\ then - 1\ else\ 0)) \wedge (if\ poly\ q\ (real\text{-}of\text{-}int\ x) < 0\ then - (1::rat) = (if\ poly\ q\ (real\text{-}of\text{-}int\ x) < 0\ then - 1\ else\ 0)\ else\ (0::rat) = (if\ poly\ q\ (real\text{-}of\text{-}int\ x) < 0\ then - 1\ else\ 0))$
by (*simp add*: *sgn-def*)
moreover
{ assume $- (1::int) \neq (if\ poly\ q\ (real\text{-}of\text{-}int\ x) < 0\ then - 1\ else\ 0)$
then have $0 < poly\ q\ (real\text{-}of\text{-}int\ x)$
using *f3* **by** (*metis* (*no-types*) *not-less-iff-gr-or-eq*) **}**
ultimately show *?thesis*
by (*smt* (*verit*) *Rat.of-rat-1 f4 of-int-hom.hom-one*)
qed
qed

lemma *limit-pos-infinity-helper2*:
assumes *q-in*: $q \in set\ qs$
assumes *qnonz*: $q = 0$
assumes $x = (crb\ (prod\text{-}list\text{-}var\ qs))$
shows $(if\ (poly\ q\ x > 0)\ then\ (1::rat)\ else\ (if\ (poly\ q\ x = 0)\ then\ (0::rat)\ else\ (-1::rat)))$
$= ((Sturm\text{-}Tarski.sign\ (sgn\text{-}pos\text{-}inf\ q))::int)$
proof −

have *0 = ((Sturm-Tarski.sign (sgn-pos-inf q)))*
by (*simp add*: *qnonz sgn-pos-inf-def*)
then show *?thesis* **using** *qnonz*
by *auto*
qed

lemma *limit-pos-infinity-helper*:
assumes *q-in*: *q ∈ set qs*
assumes *x = (crb (prod-list-var qs))*
shows (*if (poly q x > 0) then (1::int) else (if (poly q x = 0) then 0 else −1)*)
= ((Sturm-Tarski.sign (sgn-pos-inf q)))
using *limit-pos-infinity-helper1 limit-pos-infinity-helper2 assms*(*2*) *q-in*
by (*smt* (*verit*) *Rat.of-rat-1 Sturm-Tarski.sign-cases of-int-eq-iff of-int-hom.hom-one of-int-hom.hom-zero of-rat-0 of-rat-neg-one one-neq-neg-one zero-neq-neg-one*)

lemma *Sturm-Tarski-casting*:
shows ((*Sturm-Tarski.sign x*)) = *rat-of-int* (*Sturm-Tarski.sign x*)
by (*simp add*: *Sturm-Tarski.sign-def*)

lemma *limit-pos-infinity*:
shows *consistent-sign-vec qs* (*crb* (*prod-list-var qs*)) = *sgn-pos-inf-rat-list qs*
unfolding *consistent-sign-vec-def sgn-pos-inf-rat-list-def*
using *limit-pos-infinity-helper Sturm-Tarski-casting*
apply (*auto*)
apply *fastforce*
apply *presburger*
by (*metis of-int-hom.hom-one of-int-minus*)

lemma *nonzcrb-helper-neg*:
assumes *q-in*: *q ∈ set qs*
assumes *qnonz*: *q ≠ 0*
assumes *lengt*: *length* (*sorted-list-of-set* {(*x*::*real*). (∃ *q* ∈ *set*(*qs*). (*q ≠ 0 ∧ poly q x = 0*))} :: *real list*) > *0*
shows ¬(∃ *x* ≤ (*real-of-int* (−*crb* (*prod-list-var qs*))). *poly q x = 0*)
proof *clarsimp*
fix *x*
assume *xlt*: *x* ≤ − *real-of-int* (*crb* (*prod-list-var qs*))
assume *pqz*: *poly q x = 0*
let *?zer-list = sorted-list-of-set* {(*x*::*real*). (∃ *q* ∈ *set*(*qs*). (*q ≠ 0 ∧ poly q x = 0*))} :: *real list*
have *strict-sorted-h*: *sorted-wrt* (<) *?zer-list* **using** *sorted-sorted-list-of-set strict-sorted-iff* **by** *auto*
have *finset*: *finite* {*x*. ∃ *q*∈*set qs*. *q ≠ 0 ∧ poly q x = 0*}
proof −
have *all-q*: ∀ *q* ∈ *set qs*. *q*≠ *0* ⟶ *finite* {*x*. *poly q x = 0*}
using *poly-roots-finite* **by** *auto*
then show *?thesis* **by** *auto*
qed
have *all-x*: ∀ *x* ∈ {*x*. ∃ *q*∈*set qs*. *q ≠ 0 ∧ poly q x = 0*}. *poly* (*prod-list-var qs*) *x*

$= 0$
using *q-dvd-prod-list-var-prop*
by *fastforce*
then have *poly* (*prod-list-var qs*) (*sorted-list-of-set* $\{x.\ \exists\, q{\in}set\ qs.\ q \neq 0 \wedge poly\ q\ x = 0\}$! *0*) = *0*
using *finset set-sorted-list-of-set*
by (*metis* (*no-types*, *lifting*) *lengt nth-mem*)
then have *crbgt*: $-crb$ (*prod-list-var qs*) < *?zer-list* ! *0* **using** *prod-list-var-nonzero crb-lem-pos*[*of prod-list-var qs ?zer-list* ! (*length ?zer-list* − *1*)]
using *crb-lem-neg* **by** *blast*
have *x-in*: $x \in \{x.\ \exists\, q{\in}set\ qs.\ q \neq 0 \wedge poly\ q\ x = 0\}$
using *pqz q-in qnonz*
by *auto*
then have $x \in$ *set ?zer-list*
by (*smt* (*verit*, *best*) *finset mem-Collect-eq set-sorted-list-of-set*)
then have $x \geq$ *?zer-list* ! *0* **using** *strict-sorted-h*
by (*smt* (*verit*) *all-x x-in crb-lem-neg linorder-not-le of-int-hom.hom-uminus prod-list-var-nonzero xlt*)
then show *False* **using** *xlt crbgt*
by *auto*
qed

lemma *nonzcrb-neg*:
assumes *q-in*: $q \in$ *set qs*
assumes *qnonz*: $q \neq 0$
shows $\neg(\exists\, x \leq$ (*real-of-int* ($-crb$ (*prod-list-var qs*))). *poly q x* = *0*)
proof −
let *?zer-list* = (*sorted-list-of-set* $\{(x{::}real).\ (\exists\, q \in set(qs).\ (q \neq 0 \wedge poly\ q\ x = 0))\}$ :: *real list*)
have *eo*: *length ?zer-list* = *0* ∨ *length ?zer-list* > *0*
by *auto*
have *h1*: *length ?zer-list* = *0* ⟶ $\neg(\exists\, x \leq$ (*real-of-int* ($-crb$ (*prod-list-var qs*))). *poly q x* = *0*)
by (*metis crb-lem-neg dvdE linorder-not-less mult-zero-left poly-mult prod-list-var-nonzero q-dvd-prod-list-var-prop q-in qnonz*)
have *h2*: *length ?zer-list* > *0* ⟶ $\neg(\exists\, x \leq$ (*real-of-int* ($-crb$ (*prod-list-var qs*))). *poly q x* = *0*)
using *nonzcrb-helper-neg assms*
by *blast*
show *?thesis* **using** *eo h1 h2*
by *auto*
qed

lemma *root-lb-restate*:
fixes *p*:: *real poly*
assumes *pnonz*: $p \neq 0$
fixes *z*::*real*
assumes *zgt*: $\forall\, x.$ *poly p x*=*0* ⟶ $x > z$
shows $x{\leq}z \Longrightarrow$ *sgn* (*poly p x*) = *Sturm-Tarski.sign* (*sgn-neg-inf p*)

proof −
assume *xlt*: $x \leq z$
have *allx*: $\forall x \leq z.\ sgn\ (poly\ p\ x) = sgn\ (poly\ p\ z)$
proof *clarsimp*
fix x
assume *zleq*: $x \leq z$
then have *xnonz*: $sgn\ (poly\ p\ x) \neq 0$
using *zgt* **unfolding** *sgn-def* **by** *auto*
have *znonz*: $sgn\ (poly\ p\ z) \neq 0$
using *zgt* **unfolding** *sgn-def* **by** *auto*
have *Matrix-Equation-Construction.sgn* $(poly\ p\ x) \neq$ *Matrix-Equation-Construction.sgn* $(poly\ p\ z) \Longrightarrow$ *False*
proof −
assume *neq*: *Matrix-Equation-Construction.sgn* $(poly\ p\ x) \neq$ *Matrix-Equation-Construction.sgn* $(poly\ p\ z)$
then have $x < z$ **using** *zleq*
using *less-eq-real-def* **by** *force*
then have $((poly\ p\ x) > 0 \wedge (poly\ p\ z) < 0) \vee ((poly\ p\ x) < 0 \wedge (poly\ p\ z) > 0)$
using *znonz xnonz zgt neq sgn-def*
by *metis*
then have $\exists w.\ w < x \wedge w > z \wedge (poly\ p\ w = 0)$
using *poly-IVT-pos*[*of x z*] *poly-IVT-neg*[*of x z*]
by (*metis* ‹$x < z$› *not-less-iff-gr-or-eq zgt*)
then show *False*
using *zgt zleq*
by *linarith*
qed
then show *Matrix-Equation-Construction.sgn* $(poly\ p\ x) =$ *Matrix-Equation-Construction.sgn* $(poly\ p\ z)$
by *auto*
qed
have $(\exists ub.\ (\forall x \leq ub.\ sgn\text{-}class.sgn\ (poly\ p\ x) = sgn\text{-}neg\text{-}inf\ p))$
using *root-lb*[*of p*] *pnonz*
by *meson*
then obtain *lb* **where** *ub-prop*: $(\forall x \leq lb.\ sgn\text{-}class.sgn\ (poly\ p\ x) = sgn\text{-}neg\text{-}inf\ p)$
by *auto*
let *?ub2* = *min lb* $(z-1)$
have $(\forall x \leq ?ub2.\ sgn\text{-}class.sgn\ (poly\ p\ x) = sgn\text{-}neg\text{-}inf\ p) \wedge (?ub2 < z)$
using *ub-prop* **by** *auto*
then have *h1*: $(Sturm\text{-}Tarski.sign(sgn\text{-}class.sgn\ (poly\ p\ ?ub2)::real)) = Sturm\text{-}Tarski.sign(sgn\text{-}neg\text{-}inf\ p) \wedge (?ub2 < z)$
by *auto*
have $(Sturm\text{-}Tarski.sign(sgn\text{-}class.sgn\ (poly\ p\ ?ub2)::real)) = (sgn\ (poly\ p\ ?ub2))$
unfolding *sign-def sgn-def* **by** *auto*
then have $(sgn\ (poly\ p\ ?ub2)) = (Sturm\text{-}Tarski.sign(sgn\text{-}neg\text{-}inf\ p)) \wedge (?ub2 < z)$
using *h1* **by** *metis*

then show *?thesis* **using** *allx xlt*
by (*metis min.absorb3 min.cobounded2*)
qed

lemma *limit-neg-infinity-helper1*:
assumes *q-in*: $q \in set\ qs$
assumes *qnonz*: $q \neq 0$
assumes $x = -(crb\ (prod\text{-}list\text{-}var\ qs))$
shows $(if\ (poly\ q\ x > 0)\ then\ 1\ else\ (if\ (poly\ q\ x = 0)\ then\ 0\ else\ -1))$
$= ((Sturm\text{-}Tarski.sign\ (sgn\text{-}neg\text{-}inf\ q)))$
proof −
have $(\exists\, ub.\ (\forall\, x.\ poly\ q\ x = 0 \longrightarrow x < ub \longrightarrow$
$(\forall\, x{\geq}ub.\ sgn\text{-}class.sgn\ (poly\ q\ x) = sgn\text{-}neg\text{-}inf\ q)))$
using *root-lb*[*of q*] *qnonz*
by (*meson not-less-iff-gr-or-eq*)
then obtain *ub* **where** *ub-prop*: $(\forall\, x.\ poly\ q\ x = 0 \longrightarrow x < ub \longrightarrow$
$(\forall\, x{\geq}ub.\ sgn\text{-}class.sgn\ (poly\ q\ x) = sgn\text{-}neg\text{-}inf\ q))$
by *auto*
show *?thesis*
proof −
have $q \in set\ qs \wedge q \neq 0$
using ‹$q \in set\ qs$› ‹$q \neq 0$› **by** *blast*
then have *f1*: $\forall\, r.\ \neg\ r \leq real\text{-}of\text{-}int\ (-\ crb\ (prod\text{-}list\text{-}var\ qs)) \vee 0 \neq poly\ q\ r$
using *nonzcrb-neg*[*of q*] **by** *auto*
have *f2*: $real\text{-}of\text{-}int\ x \leq real\text{-}of\text{-}int\ (-\ crb\ (prod\text{-}list\text{-}var\ qs))$
using ‹$x = -\ crb\ (prod\text{-}list\text{-}var\ qs)$› **by** *fastforce*
obtain *rr* :: *real* **where**
f3: $q \neq 0 \wedge (0 = poly\ q\ rr \longrightarrow real\text{-}of\text{-}int\ (-\ crb\ (prod\text{-}list\text{-}var\ qs)) < rr) \wedge real\text{-}of\text{-}int\ x \leq real\text{-}of\text{-}int\ (-\ crb\ (prod\text{-}list\text{-}var\ qs)) \longrightarrow Sturm\text{-}Tarski.sign\ (sgn\text{-}neg\text{-}inf\ q) = Matrix\text{-}Equation\text{-}Construction.sgn\ (poly\ q\ (real\text{-}of\text{-}int\ x))$
by (*metis assms*(*2*) *root-lb-restate*[*of q*])
have $\neg\ rr \leq real\text{-}of\text{-}int\ (-\ crb\ (prod\text{-}list\text{-}var\ qs)) \vee 0 \neq poly\ q\ rr$
using *f1* **by** *blast*
then have $Sturm\text{-}Tarski.sign\ (sgn\text{-}neg\text{-}inf\ q) = Matrix\text{-}Equation\text{-}Construction.sgn\ (poly\ q\ (real\text{-}of\text{-}int\ x))$
using *f3 f2* ‹$q \neq 0$› **by** *linarith*
then show *?thesis*
by (*smt* (*verit*, *best*) *Sturm-Tarski.sign-def of-int-eq-iff of-int-hom.hom-one of-int-hom.hom-zero of-rat-hom.hom-0-iff of-rat-hom.hom-1-iff of-rat-neg-one sgn-def*)
qed

qed

lemma *limit-neg-infinity-helper2*:
assumes *q-in*: $q \in set\ qs$
assumes *qnonz*: $q = 0$
assumes $x = (-crb\ (prod\text{-}list\text{-}var\ qs))$
shows $(if\ (poly\ q\ x > 0)\ then\ 1\ else\ (if\ (poly\ q\ x = 0)\ then\ 0\ else\ -1))$
$= Sturm\text{-}Tarski.sign\ (sgn\text{-}neg\text{-}inf\ q)$

proof −
have *0 = Sturm-Tarski.sign (sgn-neg-inf q)*
by (*simp add*: *qnonz sgn-neg-inf-def*)
then show *?thesis* **using** *qnonz*
by *auto*
qed

lemma *limit-neg-infinity-helper-var*:
assumes *q-in*: *q ∈ set qs*
assumes *x = (−crb (prod-list-var qs))*
shows (*if (poly q x > 0) then 1 else (if (poly q x = 0) then 0 else −1)*)
= Sturm-Tarski.sign (sgn-neg-inf q)
using *limit-neg-infinity-helper1 limit-neg-infinity-helper2 assms*(*2*) *q-in*
by *blast*

lemma *limit-neg-infinity-helper*:
assumes *q-in*: *q ∈ set qs*
assumes *x = (−crb (prod-list-var qs))*
shows (*if (poly q x > 0) then 1 else (if (poly q x = 0) then 0 else −1)*)
= (Sturm-Tarski.sign (sgn-neg-inf q))
using *limit-neg-infinity-helper-var Sturm-Tarski-casting*[*of (sgn-neg-inf q)*]
using *assms*(*2*) *q-in* **by** *presburger*

lemma *limit-neg-infinity*:
shows *consistent-sign-vec qs (−(crb (prod-list-var qs))) = sgn-neg-inf-rat-list qs*
using *limit-neg-infinity-helper Sturm-Tarski-casting*
consistent-sign-vec-def sgn-neg-inf-rat-list-def
apply (*auto*) **apply** *fastforce* **apply** *presburger*
by (*metis* (*mono-tags*, *opaque-lifting*) *of-int-eq-1-iff of-int-minus*)

lemma *csv-signs-at-same*:
shows *consistent-sign-vec qs x = signs-at qs x*
unfolding *consistent-sign-vec-def signs-at-def squash-def* **by** *auto*

lemma *complex-real-int-casting*:
fixes *z*:: *int*
shows (*complex-of-real ∘ real-of-int*) *z = complex-of-int z*
by *auto*

lemma *poly-f-ncrb-constant-connection*:
assumes *is-const*: *check-all-const-deg qs = True*
shows *set* (*characterize-consistent-signs-at-roots* (*poly-f qs*) *qs*)
= set (*characterize-consistent-signs-at-roots* (*poly-f-nocrb qs*) *qs*) ∪ {*sgn-neg-inf-rat-list qs*, *sgn-pos-inf-rat-list qs*}
proof −
have *h1*: (*poly-f qs*) = [:*0*, *1*:]
using *assms* **unfolding** *poly-f-def* **by** *auto*
have *h2*: (*poly-f-nocrb qs*) = [:*0*, *1*:]
using *assms* **unfolding** *poly-f-nocrb-def* **by** *auto*

then have *same-set1*: *set* (*characterize-consistent-signs-at-roots* (*poly-f qs*) *qs*)
= *set* (*characterize-consistent-signs-at-roots* (*poly-f-nocrb qs*) *qs*)
using *h1 h2*
by *auto*
have {*x*. *poly* (*poly-f qs*) *x* = *0*} = {*0*}
using *h1* **by** *auto*
then have (*characterize-root-list-p* (*poly-f qs*)) = [*0*]
using *h1* **unfolding** *characterize-root-list-p-def* **by** *auto*
then have (*characterize-consistent-signs-at-roots* (*poly-f qs*) *qs*)
= (*remdups* (*map* (*signs-at qs*) [*0*]))
unfolding *characterize-consistent-signs-at-roots-def* **by** *auto*
then have (*characterize-consistent-signs-at-roots* (*poly-f qs*) *qs*) = [*signs-at qs 0*]
by *auto*
then have *same-set2*: *set* (*characterize-consistent-signs-at-roots* (*poly-f-nocrb qs*) *qs*) = {*signs-at qs 0*}
using *same-set1*
by *auto*
have *same1*: *sgn-neg-inf-rat-list qs* = *sgn-pos-inf-rat-list qs*
using *is-const* **unfolding** *sgn-neg-inf-rat-list-def sgn-pos-inf-rat-list-def*
unfolding *sgn-neg-inf-def sgn-pos-inf-def*
using *check-all-const-deg-prop* **by** *auto*
have ⋀*q*. *q* ∈ *set qs* ⟹ *poly q 0* = *lead-coeff q*
using *is-const check-all-const-deg-prop*
by (*metis poly-0-coeff-0*)
then have *same2-h*: *map* (λ*x*. *rat-of-int* (*Sturm-Tarski.sign* (*sgn-class.sgn* (*lead-coeff x*)))) *qs* =
map ((λ*x*. *if 0* < *x then 1 else if x* < *0 then* − *1 else 0*) ∘ (λ*q*. *poly q 0*)) *qs*
by *simp*
then have *map rat-of-int* (*sgn-pos-inf-rat-list qs*) = (*signs-at qs 0*)
using *is-const check-all-const-deg-prop*
unfolding *sgn-pos-inf-rat-list-def sgn-pos-inf-def signs-at-def squash-def*
by *auto*
then have *map real-of-rat* (*map rat-of-int* (*sgn-pos-inf-rat-list qs*)) =
map of-rat (*signs-at qs 0*)
by *auto*
then have *map real-of-int* (*sgn-pos-inf-rat-list qs*) = *map of-rat* (*signs-at qs 0*)
by *auto*
then have *map complex-of-real* (*map real-of-int* (*sgn-pos-inf-rat-list qs*)) = *map of-rat* (*signs-at qs 0*)
by *auto*
then have *same2*: (*sgn-pos-inf-rat-list qs*) = (*signs-at qs 0*)
using *complex-real-int-casting*
by (*metis list.map-comp map-eq-conv*)
show *?thesis*
using *same-set1 same-set2 same1 same2*
by *auto*
qed

lemma *poly-f-ncrb-nonconstant-connection*:

assumes *is-not-const*: *check-all-const-deg qs = False*
shows *set (characterize-consistent-signs-at-roots (poly-f qs) qs)*
= set (characterize-consistent-signs-at-roots (poly-f-nocrb qs) qs) ∪ {sgn-neg-inf-rat-list qs, sgn-pos-inf-rat-list qs}
proof −
let *?s1 = {x. poly (poly-f qs) x = 0}*
let *?s2 = ({x. poly (poly-f-nocrb qs) x = 0} ∪ ({−(crb (prod-list-var qs)), (crb (prod-list-var qs))}::real set))*
have *same-set*: *?s1 = ?s2*
using *root-set-nocrb-var[of qs] is-not-const*
by *auto*
then have *same-map*: *(λx. (signs-at qs x)) ‘ ?s1 = (λx. (signs-at qs x)) ‘ ?s2*
by *presburger*
have *set (characterize-consistent-signs-at-roots (poly-f qs) qs) =*
set (map (signs-at qs) (characterize-root-list-p (poly-f qs)))
using *characterize-consistent-signs-at-roots-def* **by** *auto*
then have *set (characterize-consistent-signs-at-roots (poly-f qs) qs) =*
(λx. (signs-at qs x)) ‘ {x. poly (poly-f qs) x = 0}
by (*simp add*: *characterize-root-list-p-def poly-f-nonzero poly-roots-finite*)
then have *set (characterize-consistent-signs-at-roots (poly-f qs) qs) =*
(λx. (signs-at qs x)) ‘ ({x. poly (poly-f-nocrb qs) x = 0} ∪ ({−(crb (prod-list-var qs)), (crb (prod-list-var qs))}::real set))
using *same-map* **by** *auto*
then have *bigeq*: *set (characterize-consistent-signs-at-roots (poly-f qs) qs) =*
(λx. (signs-at qs x)) ‘ {x. poly (poly-f-nocrb qs) x = 0} ∪ (λx. (signs-at qs x)) ‘ ({−(crb (prod-list-var qs)), (crb (prod-list-var qs))}::real set)
by (*metis image-Un*)
have *crb-seteq*: *(λx. (signs-at qs x)) ‘ ({−(crb (prod-list-var qs)), (crb (prod-list-var qs))}::real set) =*
(λx. (signs-at qs x)) ‘ ({−(crb (prod-list-var qs))}::real set) ∪
(λx. (signs-at qs x)) ‘ ({(crb (prod-list-var qs))}::real set)
by *blast*
have *neg*: *(λx. (signs-at qs x)) ‘ ({−(crb (prod-list-var qs))}::real set) ={sgn-neg-inf-rat-list qs}*
using *limit-neg-infinity[of qs] csv-signs-at-same* **by** *auto*
have *pos*: *(λx. (signs-at qs x)) ‘ ({(crb (prod-list-var qs))}::real set) ={sgn-pos-inf-rat-list qs}*
using *limit-pos-infinity[of qs] csv-signs-at-same* **by** *auto*
have *(λx. (signs-at qs x)) ‘ ({−(crb (prod-list-var qs)), (crb (prod-list-var qs))}::real set) = {sgn-neg-inf-rat-list qs} ∪ {sgn-pos-inf-rat-list qs}*
using *crb-seteq neg pos* **by** *auto*
then have *(λx. (signs-at qs x)) ‘ ({−(crb (prod-list-var qs)), (crb (prod-list-var qs))}::real set)*
= {sgn-neg-inf-rat-list qs, sgn-pos-inf-rat-list qs}
by *auto*
then have *biggereq*: *set (characterize-consistent-signs-at-roots (poly-f qs) qs) =*
signs-at qs ‘ {x. poly (poly-f-nocrb qs) x = 0} ∪
{sgn-neg-inf-rat-list qs, sgn-pos-inf-rat-list qs}
using *bigeq* **by** *auto*

have *key*: *signs-at qs ‘ {x. poly (poly-f-nocrb qs) x = 0} = set (characterize-consistent-signs-at-roots (poly-f-nocrb qs) qs)*
using *characterize-consistent-signs-at-roots-def Groups.mult-ac(2) characterize-root-list-p-def is-not-const list.set-map mult-cancel-left mult-cancel-left1 poly-f-def poly-f-nocrb-def poly-f-nonzero poly-roots-finite set-remdups sorted-list-of-set(1)*
proof −
have *poly-f-nocrb qs ≠ 0*
by (*metis mult-cancel-left1 poly-f-def poly-f-nocrb-def poly-f-nonzero*)
then have *set (remdups (map (signs-at qs) (sorted-list-of-set {r. poly (poly-f-nocrb qs) r = 0}))) = signs-at qs ‘ {r. poly (poly-f-nocrb qs) r = 0}*
by (*simp add*: *poly-roots-finite*)
then show *?thesis*
using *characterize-consistent-signs-at-roots-def characterize-root-list-p-def* **by** *presburger*
qed
then show *?thesis* **using** *biggereq*
by (*metis image-image list.set-map*)
qed

lemma *poly-f-ncrb-connection*:
shows *set (characterize-consistent-signs-at-roots (poly-f qs) qs)*
= set (characterize-consistent-signs-at-roots (poly-f-nocrb qs) qs) ∪ {sgn-neg-inf-rat-list qs, sgn-pos-inf-rat-list qs}
using *poly-f-ncrb-nonconstant-connection poly-f-ncrb-constant-connection*
by *blast*

end

theory *Hybrid-Multiv-Matrix-Proofs*
imports
BenOr-Kozen-Reif.Matrix-Equation-Construction
Multiv-Tarski-Query
BenOr-Kozen-Reif.Renegar-Proofs
Hybrid-Multiv-Matrix
Hybrid-Multiv-Algorithm
Renegar-Modified

begin

hide-const *BKR-Decision.And*
hide-const *BKR-Decision.Or*

hide-const *UnivPoly.eval*

17.1 Connect multivariate Tarski queries to univariate

lemma *pull-out-pairs-length*:
shows *length* (*pull-out-pairs qs Is*) = *length Is*
using *pull-out-pairs.simps* **by** *force*

lemma *construct-NofI-M-subset-prop*:
assumes (*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps qs1 qs2*)
shows *set init-assumps* ⊆ *set assumps*
proof −
have (*assumps*, *tq*) ∈ *set* (*map construct-NofI-single-M* (*construct-NofI-R-spmods p init-assumps qs1 qs2*))
using *assms*
by *auto*
then obtain *mid-assumps tq-list* **where** *tuple-prop2*: (*assumps*, *tq*) = *construct-NofI-single-M* (*mid-assumps*, *tq-list*)
(*mid-assumps*, *tq-list*) ∈ *set* (*construct-NofI-R-spmods p init-assumps qs1 qs2*)
by *force*
have *s1*: *mid-assumps* = *assumps*
using *tuple-prop2*(*1*)
by *simp*
have *s2*: *set init-assumps* ⊆ *set mid-assumps*
using *tuple-prop2*(*2*) *spmods-multiv-assum-acc*
by (*metis construct-NofI-R-spmods-def*)
then show *set init-assumps* ⊆ *set assumps*
using *s1 s2*
by *blast*
qed

17.2 Connect multivariate RHS vector to univariate

lemma *construct-rhs-vector-rec-M-subset-prop-len1*:
assumes (*assumps*, *rhs-list*) ∈ *set* (*construct-rhs-vector-rec-M p init-assumps* [*a*])
shows *set init-assumps* ⊆ *set assumps*
proof −
obtain *qs1 qs2* **where** *a-prop*: *a* = (*qs1*, *qs2*)
using *prod.exhaust* **by** *blast*
have *tuple-prop*: (*assumps*, *rhs-list*) ∈ *set* (*map* (λ(*new-assumps*, *tq*). (*new-assumps*, [*tq*])) (*construct-NofI-M p init-assumps qs1 qs2*))
using *a-prop assms* **by** *auto*
then obtain *tq* **where** *tq-prop*: *rhs-list* = [*tq*]
by *auto*
let *?ell* = (*map* (λ(*new-assumps*, *tq*). (*new-assumps*, [*tq*])) (*construct-NofI-M p init-assumps qs1 qs2*))
have *tuple-in-list*: (*assumps*, *rhs-list*) ∈ *set ?ell*
using *tuple-prop*
by *auto*
then have (*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps qs1 qs2*)
using *tq-prop*
by (*smt* (*verit*, *best*) *imageE list.inject list.set-map old.prod.case old.prod.simps*(*1*)

prod.collapse)
then have (*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps qs1 qs2*)
using *tq-prop*
by *metis*
then have (*assumps*, *tq*) ∈ *set*(*map construct-NofI-single-M*
(*construct-NofI-R-spmods p init-assumps qs1 qs2*))
by *force*
then have (*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps qs1 qs2*)
using ‹(*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps qs1 qs2*)› **by** *force*
then show *?thesis* **using** *construct-NofI-M-subset-prop*
by *blast*
qed

lemma *construct-rhs-vector-rec-M-subset-prop*:
assumes (*assumps*, *rhs-list*) ∈ *set* (*construct-rhs-vector-rec-M p init-assumps qs-list*)
shows *set init-assumps* ⊆ *set assumps*
using *assms*
proof (*induct qs-list arbitrary*: *assumps rhs-list init-assumps*)
case *Nil*
then show *?case*
using *construct-rhs-vector-rec-M.simps* **by** *auto*
next
case (*Cons a qs-list*)
obtain *qs1 qs2* **where** *a-prop*: *a* = (*qs1*, *qs2*)
using *Cons.prems Cons.hyps prod.exhaust*
by *fastforce*
{ assume ∗: *qs-list* = []
then have *set init-assumps* ⊆ *set assumps* **using** *construct-rhs-vector-rec-M-subset-prop-len1*

Cons.prems
by *blast*
}
moreover { assume ∗: *length qs-list* ≥ *1*
then obtain *v va* **where** *qs-list-prop*: *qs-list* = *v* # *va*
by (*metis One-nat-def Suc-le-length-iff*)
let *?TQ-list* = *construct-NofI-M p init-assumps qs1 qs2*
have (*assumps*, *rhs-list*) ∈ *set* (*construct-rhs-vector-rec-M p init-assumps* ((*qs1*, *qs2*)#*qs-list*))
using *Cons.prems*(*1*) ∗ *a-prop* **by** *auto*
then have (*assumps*, *rhs-list*) ∈ *set* (*concat* ((*map* (λ(*new-assumps*, *tq*).
(*let rec* = *construct-rhs-vector-rec-M p new-assumps qs-list in*
map (λ*r*. (*fst r*, *tq*#*snd r*)) *rec*)) *?TQ-list*)))
using ∗ *a-prop qs-list-prop*
by (*simp add*: *split-def*)
then obtain *new-assumps tq* **where** *tq-prop*: (*new-assumps*,*tq*) ∈ *set* (*?TQ-list*)
(*assumps*, *rhs-list*) ∈ *set* (*let rec* = *construct-rhs-vector-rec-M p new-assumps qs-list in*
map (λ*r*. (*fst r*, *tq*#*snd r*)) *rec*)

```
    by auto
  then obtain rhs-rest where rhs-list-prop: rhs-list = tq#rhs-rest
    (assumps, rhs-rest) ∈ set (construct-rhs-vector-rec-M p new-assumps qs-list)
    by auto
  then have s1: set new-assumps ⊆ set assumps
    using Cons.hyps
    by auto
  have s2: set init-assumps ⊆ set new-assumps
    using construct-NofI-M-subset-prop tq-prop(1)
    by auto
  have set init-assumps ⊆ set assumps
    using s1 s2
    by auto
 }
 ultimately show ?case
  using Cons.prems
  by (metis length-0-conv less-one linorder-neqE-nat nat-less-le rel-simps(47))
qed

lemma construct-rhs-vector-rec-M-univariate:

 assumes rhs-list-is: (assumps, rhs-list) ∈ set(construct-rhs-vector-rec-M p init-assumps
qs-list)
 assumes val: ⋀p n. (p,n) ∈ set assumps ⟹ satisfies-evaluation val p n
 shows rhs-list = map (λ(qs1,qs2).
  (construct-NofI-R (eval-mpoly-poly val p) (eval-mpoly-poly-list val qs1) (eval-mpoly-poly-list
val qs2))) qs-list
 using assms
proof (induct qs-list arbitrary: assumps rhs-list init-assumps)
 case Nil
 then show ?case
  using construct-rhs-vector-rec-M.simps
  by auto
next
 case (Cons a qs-list)
 obtain qs1 qs2 where a-prop: a = (qs1, qs2)
  using Cons.prems Cons.hyps
  using prod.exhaust by blast
 { assume ∗: qs-list = []
  let ?tq = construct-NofI-R (eval-mpoly-poly val p) (eval-mpoly-poly-list val qs1)
(eval-mpoly-poly-list val qs2)
  have (assumps, rhs-list) ∈ set (construct-rhs-vector-rec-M p init-assumps [(qs1,
qs2)])
    using Cons.prems(1) ∗ a-prop by auto
  then have
    (assumps, rhs-list) ∈ set (let TQ-list = construct-NofI-M p init-assumps qs1
qs2 in
   map (λ(new-assumps, tq). (new-assumps, [tq])) TQ-list)
    by (metis construct-rhs-vector-rec-M.simps(2))
```

then have *tuple-prop*:
(*assumps*, *rhs-list*) ∈ *set* (*map* (λ(*new-assumps*, *tq*). (*new-assumps*, [*tq*])) (*construct-NofI-M p init-assumps qs1 qs2*))
by *auto*
then obtain *tq* **where** *tq-prop*: *rhs-list* = [*tq*]
by *auto*
let *?ell* = (*map* (λ(*new-assumps*, *tq*). (*new-assumps*, [*tq*])) (*construct-NofI-M p init-assumps qs1 qs2*))
have *tuple-in-list*: (*assumps*, *rhs-list*) ∈ *set ?ell*
using *tuple-prop*
by *auto*
then have (*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps qs1 qs2*)
using *tq-prop*
by (*smt* (*verit*, *best*) *imageE list.inject list.set-map old.prod.case old.prod.simps*(*1*) *prod.collapse*)
then have (*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps qs1 qs2*)
using *tq-prop*
by *metis*
then have *rhs-list* = [*construct-NofI-R* (*eval-mpoly-poly val p*) (*eval-mpoly-poly-list val qs1*) (*eval-mpoly-poly-list val qs2*)]
using *construct-NofI-M-univariate-tarski-query*[*of assumps tq p init-assumps qs1 qs2 val*]
Cons.prems(*2*) *tq-prop*
by *auto*
then have *rhs-list* =
map (λ(*qs1*, *qs2*).
construct-NofI-R (*eval-mpoly-poly val p*) (*eval-mpoly-poly-list val qs1*)
(*eval-mpoly-poly-list val qs2*))
[(*qs1*, *qs2*)]
by *auto*
then have *rhs-list* =
map (λ(*qs1*, *qs2*).
construct-NofI-R (*eval-mpoly-poly val p*) (*eval-mpoly-poly-list val qs1*)
(*eval-mpoly-poly-list val qs2*))
(*a* # *qs-list*)
using ∗ *a-prop* **by** *auto*
}
moreover {
assume ∗: *qs-list* ≠ []
then obtain *v va* **where** *qs-list-prop*: *qs-list* = *v* # *va*
by (*meson neq-Nil-conv*)
let *?tq* = *construct-NofI-R* (*eval-mpoly-poly val p*) (*eval-mpoly-poly-list val qs1*) (*eval-mpoly-poly-list val qs2*)
let *?TQ-list* = *construct-NofI-M p init-assumps qs1 qs2*
have (*assumps*, *rhs-list*) ∈ *set* (*construct-rhs-vector-rec-M p init-assumps* ((*qs1*, *qs2*)#*qs-list*))
using *Cons.prems*(*1*) ∗ *a-prop* **by** *auto*
then have (*assumps*, *rhs-list*) ∈ *set* (*concat* ((*map* (λ(*new-assumps*, *tq*).
(*let rec* = *construct-rhs-vector-rec-M p new-assumps qs-list in*

```
    map (λr. (fst r,  tq#snd r)) rec)) ?TQ-list)))
     using ∗ a-prop qs-list-prop
     by (simp add: split-def)
  then obtain new-assumps tq where tq-prop: (new-assumps,tq) ∈ set (?TQ-list)
    (assumps, rhs-list) ∈ set (let rec = construct-rhs-vector-rec-M p new-assumps
qs-list in
    map (λr. (fst r,  tq#snd r)) rec)
     by auto
   then obtain rhs-rest where rhs-list-prop: rhs-list = tq#rhs-rest
    (assumps, rhs-rest) ∈ set (construct-rhs-vector-rec-M p new-assumps qs-list)
     by auto
   then have subset: set new-assumps ⊆ set assumps using
        construct-rhs-vector-rec-M-subset-prop[of assumps rhs-rest p new-assumps
qs-list]
     by auto
   then have val-2: ⋀ p n. (p, n) ∈ set new-assumps ⟹ satisfies-evaluation val
p n
     using val
     by (meson Set.basic-monos(7) local.Cons(3))
   have tq-is: tq = ?tq
    using construct-NofI-M-univariate-tarski-query[of new-assumps tq p init-assumps
qs1 qs2 val]
      tq-prop(1) Cons.prems(2) subset
     by blast
   have ih: rhs-rest =
         map (λ(qs1, qs2).
                construct-NofI-R (eval-mpoly-poly val p) (eval-mpoly-poly-list val
qs1)
                 (eval-mpoly-poly-list val qs2))
          qs-list
     using rhs-list-prop Cons.prems(2) val-2
     by (simp add: local.Cons(1))
   then have rhs-list =
      map (λ(qs1, qs2).
             construct-NofI-R (eval-mpoly-poly val p) (eval-mpoly-poly-list val qs1)
              (eval-mpoly-poly-list val qs2))
       (a # qs-list)
     using a-prop tq-is ih rhs-list-prop
     by simp
 }
 ultimately have rhs-list =
     map (λ(qs1, qs2).
             construct-NofI-R (eval-mpoly-poly val p) (eval-mpoly-poly-list val qs1)
              (eval-mpoly-poly-list val qs2))
       (a # qs-list)
   by blast
 then show ?case
   by blast
qed
```

lemma *retrieve-polys-prop*:
assumes $\bigwedge x.\ x \in set\ ns \Longrightarrow x < length\ qs$
shows (*eval-mpoly-poly-list val* (*retrieve-polys qs ns*)) = (*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *ns*)
using *assms* **unfolding** *eval-mpoly-poly-list-def retrieve-polys-def* **by** *auto*

lemma *construct-rhs-vector-M-univariate*:

assumes *rhs-vec-is*: (*assumps*, *rhs-vec*) ∈ *set*(*construct-rhs-vector-M p init-assumps qs Is*)
assumes $\bigwedge p\ n.$ (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *well-def-subsets*: $\bigwedge$ *Is1 Is2 n.* (*Is1*, *Is2*) ∈ *set Is* ⟹
(*n* ∈ *set Is1* ∨ *n* ∈ *set Is2*) ⟹ *n* < *length qs*
shows *rhs-vec* = *construct-rhs-vector-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) *Is*
proof −
have (*assumps*, *rhs-vec*) ∈ *set* (*map* (λ*res*. (*fst res*, *vec-of-list* (*snd res*))) (*construct-rhs-vector-rec-M p init-assumps* (*pull-out-pairs qs Is*)))
using *rhs-vec-is* **unfolding** *construct-rhs-vector-M-def* **by** *auto*
then have ∃ *rhs-list*. *rhs-vec* = *vec-of-list rhs-list* ∧ (*assumps*, *rhs-list*) ∈ *set* (*map* (λ*res*. (*fst res*, *snd res*)) (*construct-rhs-vector-rec-M p init-assumps* (*pull-out-pairs qs Is*)))
by *auto*
then obtain *rhs-list* **where** *rhs-list-prop*: *rhs-vec* = *vec-of-list rhs-list* ∧ (*assumps*, *rhs-list*) ∈ *set* (*map* (λ*res*. (*fst res*, *snd res*)) (*construct-rhs-vector-rec-M p init-assumps* (*pull-out-pairs qs Is*)))
by *auto*
then have *rhs-list-char*: *rhs-list* = *map* (λ(*qs1*,*qs2*).
(*construct-NofI-R* (*eval-mpoly-poly val p*) (*eval-mpoly-poly-list val qs1*) (*eval-mpoly-poly-list val qs2*))) (*pull-out-pairs qs Is*)
using *assms construct-rhs-vector-rec-M-univariate*

by (*smt* (*verit*, *del-insts*) *case-prod-beta map-eq-conv map-idI prod.exhaust-sel*)
have *lov-1*: *list-of-vec* (*map-vec*
(λ(*I1*, *I2*).
construct-NofI-R (*eval-mpoly-poly val p*) (*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *I1*)
(*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *I2*))
(*vec-of-list Is*)) = *map* (λ(*I1*, *I2*).
construct-NofI-R (*eval-mpoly-poly val p*) (*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *I1*)
(*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *I2*)) *Is*
by (*metis list-vec vec-of-list-map*)
have *lov-2*: *list-of-vec rhs-vec* = *rhs-list*
using *rhs-list-prop*
using *list-vec* **by** *blast*
let *?rhs-list-var* = *map* (λ(*I1*, *I2*).

construct-NofI-R (*eval-mpoly-poly val p*) (*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *I1*)
(*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *I2*)) *Is*
have *rhs-list-is*: *rhs-list* = *?rhs-list-var*
proof −
have *len-is1*: *length* (*pull-out-pairs qs Is*) = *length Is*
by *simp*
then have *length rhs-list* = *length Is*
using *rhs-list-char*
by *auto*
have *len-is2*: *length ?rhs-list-var* = *length Is*
by *auto*
have ⋀*n*. *n* < *length Is* ⟹ *rhs-list* ! *n* = *?rhs-list-var* ! *n*
proof −
fix *n*
assume ∗: *n* < *length Is*
then obtain *Is1 Is2* **where** *Is-prop*: *Is* ! *n* = (*Is1*, *Is2*)
by *fastforce*
then have (*pull-out-pairs qs Is*) ! *n* = ((*retrieve-polys qs Is1*), (*retrieve-polys qs Is2*))
using ∗ **by** *force*
then have *nth-1*: *rhs-list* ! *n* = *construct-NofI-R* (*eval-mpoly-poly val p*) (*eval-mpoly-poly-list val* (*retrieve-polys qs Is1*)) (*eval-mpoly-poly-list val* (*retrieve-polys qs Is2*))
using *rhs-list-char*
by (*simp add*: ∗ *len-is1*)
have *nth-2*: *map* (λ(*I1*, *I2*).
construct-NofI-R (*eval-mpoly-poly val p*) (*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *I1*)
(*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *I2*)) *Is* ! *n*
= *construct-NofI-R* (*eval-mpoly-poly val p*) (*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *Is1*)
(*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *Is2*)
using *Is-prop*
by (*simp add*: ∗)
have *ret-poly1*: (*eval-mpoly-poly-list val* (*retrieve-polys qs Is1*)) = (*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *Is1*)
unfolding *retrieve-polys-def eval-mpoly-poly-list-def*
using *well-def-subsets retrieve-polys-prop Is-prop*
by (*metis* ∗ *eval-mpoly-poly-list-def in-set-conv-nth retrieve-polys-def*)
have *ret-poly2*: (*eval-mpoly-poly-list val* (*retrieve-polys qs Is2*)) = (*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *Is2*)
unfolding *retrieve-polys-def eval-mpoly-poly-list-def*
using *well-def-subsets retrieve-polys-prop Is-prop*
by (*metis* ∗ *eval-mpoly-poly-list-def in-set-conv-nth retrieve-polys-def*)
have *construct-NofI-R* (*eval-mpoly-poly val p*) (*eval-mpoly-poly-list val* (*retrieve-polys qs Is1*)) (*eval-mpoly-poly-list val* (*retrieve-polys qs Is2*))
= *construct-NofI-R* (*eval-mpoly-poly val p*) (*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *Is1*)

(*retrieve-polys* (*map* (*eval-mpoly-poly val*) *qs*) *Is2*)
using *ret-poly1 ret-poly2*
by *auto*
then show *rhs-list* ! *n* = *?rhs-list-var* ! *n*
using *nth-1 nth-2* **by** *auto*
qed
then show *?thesis*
using *len-is1 len-is2*
by (*metis* ‹*length rhs-list* = *length Is*› *nth-equalityI*)
qed
then show *?thesis*
using *rhs-list-is lov-2 lov-1*
unfolding *construct-rhs-vector-R-def*
using *rhs-list-prop* **by** *force*
qed

17.3 Connect multivariate LHS vector to univariate

lemma *solve-for-lhs-vector-M-univariate*:
assumes *lhs-in*: (*assumps*, *lhs-vec*) ∈ *set* (*solve-for-lhs-M p init-assumps qs subsets matr*)
assumes *val*: ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *well-def-subsets*: ⋀ *Is1 Is2 n*. (*Is1*, *Is2*) ∈ *set subsets* ⟹
(*n* ∈ *set Is1* ∨ *n* ∈ *set Is2*) ⟹ *n* < *length qs*
shows *lhs-vec* = *solve-for-lhs-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) *subsets matr*
proof −
let *?lhs-univ* = *solve-for-lhs-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) *subsets matr*
have (*assumps*, *lhs-vec*) ∈ *set*(*map* (λ*rhs*. (*fst rhs*, *solve-for-lhs-single-M p qs subsets matr* (*snd rhs*))) (*construct-rhs-vector-M p init-assumps qs subsets*))
using *lhs-in*
using *solve-for-lhs-M-def* **by** *auto*
then obtain *rhs* **where** *rhs-prop*: *rhs* ∈ *set*(*construct-rhs-vector-M p init-assumps qs subsets*)
(*assumps*, *lhs-vec*) = (*fst rhs*, *solve-for-lhs-single-M p qs subsets matr* (*snd rhs*))
by *auto*
then have *snd-is*: *snd rhs* = *construct-rhs-vector-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) *subsets*
using *construct-rhs-vector-M-univariate*
by (*metis assms*(*2*) *fst-conv prod.collapse well-def-subsets*)
have *fst rhs* = *assumps* **using** *rhs-prop*
by *force*
have *?lhs-univ* = *mult-mat-vec* (*matr-option* (*dim-row matr*) (*mat-inverse-var matr*)) (*snd rhs*)
using *snd-is*
by (*simp add*: *solve-for-lhs-R-def*)
then show *?thesis*
using *rhs-prop*(*2*) **unfolding** *solve-for-lhs-single-M-def*

by *auto*
qed

17.4 Connect multivariate reduction step to univariate

lemma *reduce-system-single-M-univariate*:
assumes *inset*: (*assumps*, *mat-eq*) ∈ *set*(*reduce-system-single-M p qs* (*init-assumps*, *init-mat-eq*))
assumes *val*: ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *init*: *init-mat-eq* = (*m*, (*subs*, *signs*))
assumes *well-def-subsets*: ⋀ *Is1 Is2 n*. (*Is1*, *Is2*) ∈ *set subs* ⟹
(*n* ∈ *set Is1* ∨ *n* ∈ *set Is2*) ⟹ *n* < *length qs*
shows *mat-eq* = *reduce-system-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *qs*), *init-mat-eq*)
proof −
have (*assumps*, *mat-eq*) ∈ *set* (*map* (λ*lhs*. (*fst lhs*, *reduction-step-R m signs subs* (*snd lhs*))) (*solve-for-lhs-M p init-assumps qs subs m*))
using *inset*
using *assms*(*3*)
by *force*
then obtain *lhs* **where** *lhs-prop*: *lhs* ∈ *set* (*solve-for-lhs-M p init-assumps qs subs m*)
(*assumps*, *mat-eq*) = (*fst lhs*, *reduction-step-R m signs subs* (*snd lhs*))
by *auto*
then have *snd lhs* = *solve-for-lhs-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) *subs m*
using *solve-for-lhs-vector-M-univariate assms*
by (*smt* (*verit*, *best*) *prod.exhaust-sel prod.simps*(*1*))
then have *mat-eq* = *reduction-step-R m signs subs* (*solve-for-lhs-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) *subs m*)
using *lhs-prop*
by *force*
then show *?thesis*
using *init*
using *reduce-system-R.simps* **by** *presburger*
qed

lemma *reduce-system-M-univariate*:
assumes (*assumps*, *mat-eq*) ∈ *set*(*reduce-system-M p qs input-list*)
assumes *val*: ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *val-qs*: *val-qs* = (*map* (*eval-mpoly-poly val*) *qs*)
assumes *all-subsets-well-def*: ⋀ *init-assumps init-mat-eq Is1 Is2 n subs m signs*.

(*init-assumps*, (*m*, (*subs*, *signs*))) ∈ *set input-list* ⟹
(*Is1*, *Is2*) ∈ *set subs* ⟹ (*n* ∈ *set Is1* ∨ *n* ∈ *set Is2*) ⟹ *n* < *length qs*
obtains *acc mss* **where**
(*acc*,*mss*) ∈ *set* (*input-list*)
mat-eq = *reduce-system-R* (*eval-mpoly-poly val p*) (*val-qs*,*mss*)
proof −

have (*assumps*, *mat-eq*) ∈ *set*(*concat* (*map* (*reduce-system-single-M p qs*) *input-list*))
by (*metis assms*(*1*) *reduce-system-M.simps*)
then obtain *init-assumps init-m init-subs init-signs* **where**
mat-eq-prop:
(*init-assumps*, (*init-m*, (*init-subs*, *init-signs*))) ∈ *set input-list*
(*assumps*, *mat-eq*) ∈ *set* (*reduce-system-single-M p qs* (*init-assumps*, (*init-m*, (*init-subs*, *init-signs*))))
by *auto*
then have *well-def-subsets*: ⋀ *Is1 Is2 n*. (*Is1*, *Is2*) ∈ *set init-subs* ⟹ (*n* ∈ *set Is1* ∨ *n* ∈ *set Is2*) ⟹ *n* < *length qs*
using *all-subsets-well-def*
by *blast*
then have *mat-eq-is*: *mat-eq* = *reduce-system-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *qs*), (*init-m*, (*init-subs*, *init-signs*)))
using *reduce-system-single-M-univariate mat-eq-prop assms*(*2*) **by** *blast*
then show *?thesis* **using** *mat-eq-prop*
using *assms*(*3*) *that* **by** *blast*
qed

lemma *base-case-info-M-well-def*:
assumes (*init-assumps*, (*m*, (*subs*, *signs*))) ∈ *set base-case-info-M*
assumes (*Is1*, *Is2*) ∈ *set subs*
assumes *n* ∈ *set Is1* ∨ *n* ∈ *set Is2*
shows *n* < *1*
proof −
have (*m*, (*subs*, *signs*)) = *base-case-info-R* **using** *assms*(*1*)
unfolding *base-case-info-M-def* **using** *Renegar-Algorithm.base-case-info-R-def Renegar-Algorithm.base-case-info-R-def*
by *simp*
then have *s*: *subs* = [([], []),([*0*], []),([], [*0*])] **unfolding** *base-case-info-R-def*
by *auto*
have (*n* ∈ *set Is1* ∨ *n* ∈ *set Is2*) **using** *assms*(*3*)
by (*simp add*:)
thus *?thesis* **using** *assms*(*2*) **unfolding** *s* **by** *auto*
qed

17.5 Connect multivariate combining systems to univariate

lemma *base-case-with-assumps-info-M-well-def*:
assumes (*init-assumps*, (*m*, (*subs*, *signs*))) ∈ *set* (*base-case-info-M-assumps a*)
assumes (*Is1*, *Is2*) ∈ *set subs*
assumes *n* ∈ *set Is1* ∨ *n* ∈ *set Is2*
shows *n* < *1*
proof −
have (*m*, (*subs*, *signs*)) = *base-case-info-R* **using** *assms*(*1*)
unfolding *base-case-info-M-assumps-def*
using *Renegar-Algorithm.base-case-info-R-def Renegar-Algorithm.base-case-info-R-def*
by *auto*

then have *s*: *subs* = [([], []),([*0*], []),([], [*0*])] **unfolding** *base-case-info-R-def*
by *auto*
have (*n* ∈ *set Is1* ∨ *n* ∈ *set Is2*) **using** *assms*(*3*)
by (*simp add*:)
thus *?thesis* **using** *assms*(*2*) **unfolding** *s* **by** *auto*
qed

lemma *concat-map-in-set*:
assumes *x* ∈ *set* (*concat* (*map f ls*))
shows ∃ *i* < *length ls*. *x* ∈ *set* (*f* (*ls* ! *i*))
using *assms*
by (*smt* (*verit*, *best*) *in-set-conv-nth length-map map-nth-eq-conv nth-concat-split*)

lemma *combine-systems-R-snd*:
assumes *length qs1* = *length new-qs1*
shows *snd* (*combine-systems-R p* (*qs1*, *sys1*) (*qs2*, *sys2*)) =
snd (*combine-systems-R new-p* (*new-qs1*, *sys1*) (*new-qs2*, *sys2*))
proof −
obtain *m1 sub1 sgn1* **where** *sys1*: *sys1* = (*m1*, *sub1*, *sgn1*)
using *prod-cases3* **by** *blast*
obtain *m2 sub2 sgn2* **where** *sys2*: *sys2* = (*m2*, *sub2*, *sgn2*)
using *prod-cases3* **by** *blast*
have *h1*: *snd* (*combine-systems-R p* (*qs1*, *sys1*) (*qs2*, *sys2*)) =
snd (*smash-systems-R p qs1 qs2 sub1 sub2 sgn1 sgn2 m1 m2*)
using *sys1 sys2* **by** *auto*
have *h2*: *snd* (*combine-systems-R new-p* (*new-qs1*, *sys1*) (*new-qs2*, *sys2*)) =
snd (*smash-systems-R new-p new-qs1 new-qs2 sub1 sub2 sgn1 sgn2 m1 m2*)
using *sys1 sys2* **by** *auto*
show *?thesis*
using *h1 h2 assms* **unfolding** *smash-systems-R-def* **by** *auto*
qed

17.6 Subset Properties

lemma *construct-rhs-vector-M-subset-prop*:
assumes (*assumps*, *rhs-vec*) ∈ *set* (*construct-rhs-vector-M p init-assumps qs subsets*)
shows *set init-assumps* ⊆ *set assumps*
proof −
obtain *rhs-list* **where** (*assumps*, *rhs-list*) ∈ *set* (*construct-rhs-vector-rec-M p init-assumps* (*pull-out-pairs qs subsets*))
rhs-vec = *vec-of-list rhs-list*
using *assms* **unfolding** *construct-rhs-vector-M-def* **by** *auto*
then show *?thesis*
using *construct-rhs-vector-rec-M-subset-prop* **by** *auto*
qed

lemma *construct-lhs-vector-rec-M-subset-prop*:

assumes (*assumps*, *lhs-list*) ∈ *set* (*solve-for-lhs-M p init-assumps qs subsets matr*)
shows *set init-assumps* ⊆ *set assumps*
proof −
obtain *rhs-vec* **where** (*assumps*, *rhs-vec*) ∈ *set* (*construct-rhs-vector-M p init-assumps qs subsets*)
lhs-list = *matr-option* (*dim-row matr*) (*mat-inverse-var matr*) $*_v$ *rhs-vec*
using *assms* **unfolding** *solve-for-lhs-M-def solve-for-lhs-single-M-def*
by *auto*
then show *?thesis*
using *construct-rhs-vector-M-subset-prop*[*of assumps*] **by** *auto*
qed

lemma *reduce-system-single-M-subset-prop*:
assumes (*assumps*, *mat-eq*) ∈ *set* (*reduce-system-single-M p qs* (*init-assumps*, (*m*,*subs*,*signs*)))
shows *set init-assumps* ⊆ *set assumps*
proof −
obtain *lhs-vec* **where** (*assumps*, *lhs-vec*) ∈ *set* (*solve-for-lhs-M p init-assumps qs subs m*)
mat-eq = *reduction-step-R m signs subs lhs-vec*
using *assms*
by (*auto*)
then show *?thesis*
using *construct-lhs-vector-rec-M-subset-prop*[*of assumps*]
by *auto*
qed

lemma *calculate-data-assumps-M-subset*:
assumes (*assumps*, *mat-eq*) ∈ *set* (*calculate-data-assumps-M p qs init-assumps*)
shows *set init-assumps* ⊆ *set assumps*
using *assms*
proof (*induction length qs arbitrary*: *qs assumps mat-eq rule*: *less-induct*)
case *less*
{assume ∗: *length qs* = *0*
then have (*assumps*, *mat-eq*) ∈ *set* (*map* (λ(*assumps*,(*a*,(*b*,*c*))). (*assumps*, (*a*,*b*,*map* (*drop 1*) *c*))) (*reduce-system-M p* [*1*] (*base-case-info-M-assumps init-assumps*)))
using *less.prems* **by** *auto*
then obtain *a b c* **where** (*assumps*, (*a*, (*b*, *c*))) ∈ *set* (*reduce-system-M p* [*1*] (*base-case-info-M-assumps init-assumps*))
by *auto*
then have (*assumps*, (*a*, (*b*, *c*))) ∈ *set* (*concat* (*map* (*reduce-system-single-M p* [*1*]) [(*init-assumps*, *base-case-info-R*)]))
unfolding *base-case-info-M-assumps-def*
using *Renegar-Algorithm.base-case-info-R-def Renegar-Algorithm.base-case-info-R-def*

by (*auto*)
then have (*assumps*, (*a*, (*b*, *c*))) ∈ *set*(*reduce-system-single-M p* [*1*] (*init-assumps*, *base-case-info-R*))

```
    by auto
  then have set init-assumps ⊆ set assumps
    unfolding base-case-info-R-def
  using reduce-system-single-M-subset-prop[of assumps (a, (b, c)) p [1] init-assumps]
    by auto
 }
 moreover {assume ∗: length qs = 1
  then have (assumps, mat-eq) ∈ set (reduce-system-M p qs (base-case-info-M-assumps
init-assumps))
    using less.prems by auto
  then obtain a b c where (assumps, (a, (b, c))) ∈ set (reduce-system-M p qs
(base-case-info-M-assumps init-assumps))
    by (smt (verit) prod.sel(2) prod-cases4)
  then have (assumps, (a, (b, c))) ∈ set (concat (map (reduce-system-single-M
p qs) [(init-assumps, base-case-info-R)]))
    unfolding base-case-info-M-assumps-def
  using Renegar-Algorithm.base-case-info-R-def Renegar-Algorithm.base-case-info-R-def

    by (auto)
  then have (assumps, (a, (b, c))) ∈ set( reduce-system-single-M p qs (init-assumps,
base-case-info-R))
    by auto
  then have set init-assumps ⊆ set assumps
    unfolding base-case-info-R-def
  using reduce-system-single-M-subset-prop[of assumps (a, (b, c)) p qs init-assumps]
    by auto
 }
 moreover {assume ∗: length qs > 1
  let ?len = length qs
  let ?q1 = take (?len div 2) qs
  let ?left = calculate-data-assumps-M p ?q1 init-assumps
  let ?q2 = drop (?len div 2) qs
  let ?right = calculate-data-assumps-M p ?q2 init-assumps
  let ?comb = combine-systems-M p ?q1 ?left ?q2 ?right
  have len-q1-less: length ?q1 < length qs
    using ∗ by auto
  have inset-red: (assumps, mat-eq) ∈ set(reduce-system-M p (fst ?comb) (snd
?comb))
    using ∗ less.prems
      by (smt (verit, best) calculate-data-assumps-M.simps less-one nat-less-le
not-one-less-zero)
  have fst ?comb = qs
    by auto
  then have (assumps, mat-eq) ∈ set(reduce-system-M p qs (snd ?comb))
    using inset-red
    by auto
  then obtain assm-pre m-pre subs-pre signs-pre where assumps-reduce:
    (assm-pre, (m-pre, subs-pre, signs-pre)) ∈ set (snd ?comb)
      (assumps, mat-eq) ∈ set(reduce-system-single-M p qs (assm-pre, (m-pre,
```

subs-pre, *signs-pre*)))
by (*metis concat-map-in-set find-consistent-signs-at-roots-single-M.cases nth-mem reduce-system-M.simps*)
then obtain *meq1 meq2 assm1 assm2* **where** *subsystems*:
(*assm1*, *meq1*) ∈ *set* (*calculate-data-assumps-M p ?q1 init-assumps*)
(*assm2*, *meq2*) ∈ *set* (*calculate-data-assumps-M p ?q2 init-assumps*)
(*assm-pre*, (*m-pre*, *subs-pre*, *signs-pre*)) = *combine-systems-single-M p ?q1* (*assm1*, *meq1*) *?q2* (*assm2*, *meq2*)
by *auto*
then have *assm-pre*: *assm-pre* = *assm1*@*assm2*
by *auto*
have *set init-assumps* ⊆ *set assm1*
using *less.hyps*[*of ?q1*] *less.prems subsystems*(*1*) *len-q1-less*
by *auto*
then have *set init-assumps* ⊆ *set assm-pre*
using *assm-pre* **by** *auto*
then have *set init-assumps* ⊆ *set assumps*
using *assumps-reduce*(*2*) *reduce-system-single-M-subset-prop*[*of assumps mat-eq p qs assm-pre m-pre subs-pre signs-pre*]
by *auto*
}
ultimately show *?case*
by (*meson less-one linorder-neqE-nat*)
qed

lemma *extract-signs-M-subset*:
assumes (*assumps*, *signs*) ∈ *set* (*extract-signs* (*calculate-data-assumps-M p qs init-assumps*))
shows *set init-assumps* ⊆ *set assumps*
proof −
obtain *mat-eq* **where**
(*assumps*, *mat-eq*) ∈ *set* (*calculate-data-assumps-M p qs init-assumps*)
signs = *snd* (*snd mat-eq*)
using *assms* **by** *auto*
then show *?thesis*
using *calculate-data-assumps-M-subset*[*of assumps mat-eq p qs init-assumps*]
by *auto*
qed

17.7 Top-level Results: Connect calculate data methods to univariate

lemma *all-list-constr-R-matches-well-def*:
assumes *welldef*: *all-list-constr-R subs* (*length q*)
shows (*Is1*, *Is2*) ∈ *set* (*subs*) ⟹ *n* ∈ *set Is1* ∨ *n* ∈ *set Is2* ⟹ *n* < *length q*
proof −
assume *inset*: (*Is1*, *Is2*) ∈ *set* (*subs*)
assume *inlist*: *n* ∈ *set Is1* ∨ *n* ∈ *set Is2*
have *welldef-var*: ∀ *x*. *x* ∈ *set subs* ⟶

list-constr (*fst x*) (*length q*) ∧ *list-constr* (*snd x*) (*length q*)
using *welldef* **unfolding** *all-list-constr-R-def*
by (*simp add*:)
have (*Is1*, *Is2*) ∈ *set subs*
using *inset* **by** *auto*
then have (∀ *x*∈*set Is1*. *x* < *length q*) ∧ (∀ *x*∈*set Is2*. *x* < *length q*)
using *welldef-var*
by (*simp add*: *Ball-set list-constr-def*)
then show *n* < *length q*
using *inlist*
by *metis*
qed

lemma *calculate-data-M-univariate*:
assumes *mat-eq*: (*assumps*, *mat-eq*) ∈ *set* (*calculate-data-M p qs*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *p-nonzero*: *eval-mpoly-poly val p* ≠ *0*
shows *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) = *mat-eq*
using *assms*
proof (*induct length qs arbitrary*: *val p mat-eq assumps qs rule*: *less-induct*)
case (*less qs val p mat-eq assumps*)
have *length qs* = *0* ∨ *length qs* = *1* ∨ *length qs* > *1*
by (*meson less-one nat-neq-iff*)
moreover {assume ∗: *length qs* = *0*
let *?m* = (*mat-of-rows-list 3* [[*1*,*1*,*1*], [*0*,*1*,*0*], [*1*,*0*,−*1*]])
let *?subs* = [([], []),([*0*], []),([], [*0*])]
let *?signs* = [[*1*],[*0*],[−*1*]]
let *?eval-p* = *eval-mpoly-poly val p*
have *mat-eq-in*: (*assumps*, *mat-eq*) ∈ *set* (*calculate-data-M p* [])
using ∗ *less.prems*(*1*) **by** *auto*
let *?map-base* = *map* (λ(*assumps*,(*a*,(*b*,*c*))). (*assumps*, (*a*,*b*,*map* (*drop 1*) *c*))) (*reduce-system-M p* [*1*] *base-case-info-M*)
have (*assumps*, *mat-eq*) ∈ *set ?map-base*
using *mat-eq-in*
by *auto*
then obtain *a1 b1 c1* **where** *a1b1c1-prop*:
(*assumps*, (*a1*, (*b1*, *c1*))) ∈ *set* (*reduce-system-M p* [*1*] *base-case-info-M*)
mat-eq = (*a1*, (*b1*, *map* (*drop 1*) *c1*))
by *auto*
have *base-case-well-def*: ⋀*init-assumps init-mat-eq Is1 Is2 n subs m signs*.
(*init-assumps*, *m*, *subs*, *signs*) ∈ *set base-case-info-M* ⟹
(*Is1*, *Is2*) ∈ *set subs* ⟹ *n* ∈ *set Is1* ∨ *n* ∈ *set Is2* ⟹ *n* < *length* [*1*]
using *base-case-info-M-well-def* **by** *auto*
have *map-is*: [*1*] = *map* (*eval-mpoly-poly val*) [*1*]
unfolding *eval-mpoly-poly-def eval-mpoly-def*
by *auto*
then have ∃ *acc mss*. (*acc*,*mss*) ∈ *set* (*base-case-info-M*) ∧ (*a1*, (*b1*, *c1*)) = *reduce-system-R* (*eval-mpoly-poly val p*) ([*1*],*mss*)

using *reduce-system-M-univariate*[*of assumps* (*a1*, *b1*, *c1*) *p* [*1*] *base-case-info-M val* [*1*]]
a1b1c1-prop less(*3*) *base-case-well-def*
apply (*auto*)
by *metis*
then obtain *acc mss* **where** *a1b1c1-connect*:
(*acc*,*mss*) ∈ *set* (*base-case-info-M*)
(*a1*, (*b1*, *c1*)) = *reduce-system-R* (*eval-mpoly-poly val p*) ([*1*],*mss*)
by *auto*
then have *mss-is*: *mss* = *base-case-info-R*
unfolding *base-case-info-M-def*
by *auto*
obtain *a b c* **where** *abc-prop*: (*a*, *b*, *c*) = *reduction-step-R ?m ?signs ?subs* (*solve-for-lhs-R ?eval-p* [*1*] *?subs ?m*)
by (*metis reduction-step-R.simps*)
then have (*a*, *b*, *c*) = (*a1*, *b1*, *c1*)
using *abc-prop a1b1c1-prop*
by (*metis a1b1c1-connect*(*2*) *base-case-info-R-def mss-is reduce-system-R.simps*)

then have *mat-eq-is*: (*a*, *b*, *map* (*drop* (*Suc 0*)) *c*) = *mat-eq*
using *a1b1c1-prop*(*2*) **by** (*auto*)
have *qs* = [] ⟹ *mat-eq* = (*a*, *b*, *map* (*drop* (*Suc 0*)) *c*) ⟹
(*case reduce-system-R* (*eval-mpoly-poly val p*) ([*1*], *base-case-info-R*) *of*
(*a*, *b*, *c*) ⇒ (*a*, *b*, *map* (*drop* (*Suc 0*)) *c*)) = (*a*, *b*, *map* (*drop* (*Suc 0*)) *c*)
using *abc-prop* **unfolding** *base-case-info-R-def*
using *old.prod.case reduce-system-R.simps*
by (*smt* (*verit*, *ccfv-SIG*))
then have *calculate-data-R ?eval-p* (*map* (*eval-mpoly-poly val*) *qs*)= *mat-eq*
using ∗ *mat-eq-is*
by *simp*
}
moreover {**assume** ∗: *length qs* = *1*
have *meq*: (*assumps*, *mat-eq*) ∈ *set* (*reduce-system-M p qs base-case-info-M*)
using ∗ *le-eq-less-or-eq less*(*2*) *one-neq-zero* **by** *auto*
have ∗∗: ⋀*init-assumps init-mat-eq Is1 Is2 n subs m signs*.
(*init-assumps*, *m*, *subs*, *signs*) ∈ *set base-case-info-M* ⟹
(*Is1*, *Is2*) ∈ *set subs* ⟹
n ∈ *set Is1* ∨ *n* ∈ *set Is2* ⟹
n < *length qs* **unfolding** ∗
using *base-case-info-M-well-def*
by *meson*
from *reduce-system-M-univariate*[*OF meq less*(*3*), *of map* (*eval-mpoly-poly val*) *qs*]
obtain *acc mss* **where** *ams*: (*acc*,*mss*) ∈ *set base-case-info-M*
mat-eq = *reduce-system-R* (*eval-mpoly-poly val p*)
(*map* (*eval-mpoly-poly val*) *qs*, *mss*)
using ∗∗ **by** *blast*
then have *mss* = *base-case-info-R* **unfolding** *base-case-info-M-def*
by *auto*

then have *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) = *mat-eq*
using *ams* ∗ **by** *simp*
}

moreover {assume ∗: *length qs* > *1*
have *inset*: (*assumps*, *mat-eq*) ∈ *set* (*calculate-data-M p qs*)
using *less.prems*(*1*) **by** *auto*
let *?len* = *length qs*
let *?q1* = *take* (*?len div 2*) *qs*
let *?q2* = *drop* (*?len div 2*) *qs*
let *?left* = *calculate-data-M p ?q1*
let *?right* = *calculate-data-M p ?q2*
let *?comb* = *combine-systems-M p ?q1 ?left ?q2 ?right*
let *?eval-p* = (*eval-mpoly-poly val p*)
let *?eval-q1* = (*map* (*eval-mpoly-poly val*) *?q1*)
let *?eval-q2* = (*map* (*eval-mpoly-poly val*) *?q2*)
have *map-q1*: *map* (*eval-mpoly-poly val*) *?q1* =
(*take* (*length* (*map* (*eval-mpoly-poly val*) *qs*) *div 2*) (*map* (*eval-mpoly-poly val*) *qs*))
by (*auto simp add*: *take-map*)
have *map-q2*: *map* (*eval-mpoly-poly val*) *?q2* =
(*drop* (*length* (*map* (*eval-mpoly-poly val*) *qs*) *div 2*) (*map* (*eval-mpoly-poly val*) *qs*))
by (*auto simp add*: *drop-map*)
have *fst ?comb* = *qs*
by *auto*
then have (*assumps*, *mat-eq*) ∈ *set* (*reduce-system-M p qs* (*snd ?comb*))
using *inset* ∗
by (*smt* (*verit*) *calculate-data-M.simps less-numeral-extra*(*2*) *less-one nat-less-le*)
then have (*assumps*, *mat-eq*) ∈ *set* (*concat* (*map* (*reduce-system-single-M p qs*) (*snd ?comb*)))
by (*metis reduce-system-M.simps*)
then have ∃ *sys*. *sys* ∈ *set* (*snd ?comb*) ∧ (*assumps*, *mat-eq*) ∈ *set*(*reduce-system-single-M p qs sys*)
using *concat-map-in-set*
by (*metis nth-mem*)
then obtain *a-pre me-pre* **where** *reduce-prop*: (*a-pre*, *me-pre*) ∈ *set* (*snd ?comb*)
(*assumps*, *mat-eq*) ∈ *set*(*reduce-system-single-M p qs* (*a-pre*, *me-pre*))
by *fastforce*
then obtain *a1 me1 a2 me2* **where** *mes-prop*: (*a1*, *me1*) ∈ *set ?left*
(*a2*, *me2*) ∈ *set ?right*
(*a-pre*, *me-pre*) = *combine-systems-single-M p ?q1* (*a1*, *me1*) *?q2* (*a2*, *me2*)
by *auto*
then have *a-pre*: *a-pre* = *a1*@*a2*
by *auto*
have *lengt*: *length qs div 2* ≥ *1*
using ∗ **by** *auto*

then have *len-q1*: *length ?q1 < length qs*
by *auto*
have *len-q2*: *length ?q2 < length qs*
using *lengt* **by** *auto*
obtain *mat-pre subs-pre signs-pre* **where** *me-decomp*:
me-pre = (mat-pre,subs-pre,signs-pre)
using *mes-prop*
using *prod-cases3* **by** *blast*
then have *assumps ∈ set (map fst (solve-for-lhs-M p a-pre qs subs-pre mat-pre))*
using *reduce-prop(2)* **by** *auto*
then have *assumps ∈ set (map fst (construct-rhs-vector-M p a-pre qs subs-pre))*
unfolding *solve-for-lhs-M-def* **by** *auto*
then obtain *a-rhs-list* **where** *(assumps, a-rhs-list)*
∈ set (construct-rhs-vector-rec-M p a-pre (pull-out-pairs qs subs-pre))
unfolding *construct-rhs-vector-M-def* **by** *auto*
then have *a-pre-subset*: *set a-pre ⊆ set assumps*
using *construct-rhs-vector-rec-M-subset-prop[of assumps - p a-pre (pull-out-pairs qs subs-pre)]*
by *auto*
have *set-a1*: *set a1 ⊆ set assumps*
using *a-pre-subset a-pre* **by** *auto*
then have *a1-satisfies*: *(⋀p n. (p, n) ∈ set a1 ⟹ satisfies-evaluation val p n)*
using *less(3)* **by** *blast*
from *less.hyps[of ?q1 a1 me1, OF len-q1 mes-prop(1) a1-satisfies]*
have *me1-ind*: *calculate-data-R (eval-mpoly-poly val p) (map (eval-mpoly-poly val) ?q1) = me1*
using *less(4)* **by** *blast*
have *set-a2*: *set a2 ⊆ set assumps*
using *a-pre-subset a-pre* **by** *auto*
then have *a2-satisfies*: *(⋀p n. (p, n) ∈ set a2 ⟹ satisfies-evaluation val p n)*
using *less(3)* **by** *blast*
from *less.hyps[of ?q2 a2 me2, OF len-q2 mes-prop(2) a2-satisfies]*
have *me2-ind*: *calculate-data-R ?eval-p (map (eval-mpoly-poly val) ?q2) = me2*
using *less(4)* **by** *blast*
have *a-pre = a1 @ a2 ⟹ me-pre =*
snd (combine-systems-R p (take (length qs div 2) qs, me1)
(drop (length qs div 2) qs, me2)) ⟹
snd (combine-systems-R p (take (length qs div 2) qs, me1)
(drop (length qs div 2) qs, me2)) =
snd (combine-systems-R (eval-mpoly-poly val p)
(map (eval-mpoly-poly val) (take (length qs div 2) qs), me1)
(map (eval-mpoly-poly val) (drop (length qs div 2) qs), me2))
using *combine-systems-R-snd*
by *(metis length-map)*
then have *me-pre*: *me-pre = snd (combine-systems-R (eval-mpoly-poly val p) ((map (eval-mpoly-poly val) ?q1), me1) ((map (eval-mpoly-poly val) ?q2), me2))*
using *mes-prop(3)*
by *(auto)*
obtain *mat-pre1 subs-pre1 signs-pre1* **where** *me1-decomp*:

me1 = (*mat-pre1*,*subs-pre1*,*signs-pre1*)
using *prod-cases3* **by** *blast*
obtain *mat-pre2 subs-pre2 signs-pre2* **where** *me2-decomp*:
me2 = (*mat-pre2*,*subs-pre2*,*signs-pre2*)
using *prod-cases3* **by** *blast*
have *fst-comb*: *fst* (*combine-systems-R ?eval-p* ((*map* (*eval-mpoly-poly val*) *?q1*), *me1*) ((*map* (*eval-mpoly-poly val*) *?q2*), *me2*)) = (*map* (*eval-mpoly-poly val*) *?q1*) @ (*map* (*eval-mpoly-poly val*) *?q2*)
proof −
have *fst* (*combine-systems-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *?q1*), *me1*) ((*map* (*eval-mpoly-poly val*) *?q2*), *me2*)) =
fst (*smash-systems-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *?q1*) (*map* (*eval-mpoly-poly val*) *?q2*) *subs-pre1 subs-pre2 signs-pre1 signs-pre2 mat-pre1 mat-pre2*)
using *combining-to-smash-R me1-decomp me2-decomp* **by** *force*
then show *?thesis*
unfolding *smash-systems-R-def* **by** *auto*
qed
then have *map* (*eval-mpoly-poly val*) *qs* = *fst* (*combine-systems-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *?q1*), *me1*) ((*map* (*eval-mpoly-poly val*) *?q2*), *me2*))
by (*metis append-take-drop-id map-append*)
then have *me-pre-var*: (*map* (*eval-mpoly-poly val*) *qs*, *me-pre*) = (*combine-systems-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *?q1*), *me1*) ((*map* (*eval-mpoly-poly val*) *?q2*), *me2*))
using *me-pre* **by** *auto*
have *len-hyp*: *length* (*map* (*eval-mpoly-poly val*) *qs*) > *1*
using ∗ **by** *auto*
have *len-eq*: *length* (*map* (*eval-mpoly-poly val*) *qs*) = *length qs*
by *simp*
have *len-q1-gt0*: *length* (*map* (*eval-mpoly-poly val*) *?q1*) > *0*
using *len-hyp len-eq* **by** *auto*
have *len-q2-gt0*: *length* (*map* (*eval-mpoly-poly val*) *?q2*) > *0*
using *len-hyp len-eq* **by** *auto*
let *?uni-sys-q1* = *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *?q1*)
have *sat-props-q1-univ*: *satisfies-properties-R ?eval-p* (*map* (*eval-mpoly-poly val*) *?q1*) (*get-subsets-R ?uni-sys-q1*) (*get-signs-R ?uni-sys-q1*) (*get-matrix-R ?uni-sys-q1*)
using *calculate-data-satisfies-properties-R*[*of ?eval-p* (*map* (*eval-mpoly-poly val*) (*take* (*length qs div 2*) *qs*))]
len-q1-gt0 **using** *less.prems*(*3*) **by** *auto*
let *?uni-sys-q2* = *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *?q2*)
have *sat-props-q2-univ*: *satisfies-properties-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *?q2*) (*get-subsets-R ?uni-sys-q2*) (*get-signs-R ?uni-sys-q2*) (*get-matrix-R ?uni-sys-q2*)
using *calculate-data-satisfies-properties-R*[*of* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) (*drop* (*length qs div 2*) *qs*))]
len-q2-gt0 **using** *less.prems*(*3*) **by** *auto*

have *comb-satisfies*: *satisfies-properties-R ?eval-p* (*?eval-q1*@(*map* (*eval-mpoly-poly val*) *?q2*))
(*get-subsets-R* (*snd* ((*combine-systems-R ?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))))

(*get-signs-R* (*snd* ((*combine-systems-R ?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))))

(*get-matrix-R* (*snd* ((*combine-systems-R ?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))))
using *combining-sys-satisfies-properties-R*[*of ?eval-p ?eval-q1 ?eval-q2*] *len-q1-gt0 len-q2-gt0 less.prems*(*3*)
sat-props-q2-univ sat-props-q1-univ
by *auto*
then have *well-def-subs-pre*: *all-list-constr-R* (*get-subsets-R* (*snd* ((*combine-systems-R ?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))) (*length* (*?eval-q1*@*?eval-q2*))
unfolding *satisfies-properties-R-def* **by** *auto*
have *get-subs-pre*: (*get-subsets-R* (*snd* ((*combine-systems-R ?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))) = *subs-pre*
using *me-decomp* **unfolding** *get-subsets-R-def*
by (*metis fst-conv me1-ind me2-ind me-pre-var snd-conv*)
have *well-def*: (⋀*Is1 Is2 n*. (*Is1*, *Is2*) ∈ *set* (*fst* (*snd me-pre*)) ⟹ *n* ∈ *set Is1* ∨ *n* ∈ *set Is2* ⟹ *n* < *length qs*)
using *well-def-subs-pre get-subs-pre*
all-list-constr-R-matches-well-def[*of subs-pre*]
by (*smt* (*verit*, *ccfv-SIG*) *fst-comb fst-conv get-subsets-R-def length-map me1-ind me2-ind me-pre-var snd-conv*)
then have *reduce-mat-eq*: *mat-eq* = *reduce-system-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *qs*), *me-pre*)
using *reduce-system-single-M-univariate*[*OF reduce-prop*(*2*) *less.prems*(*2*)]
by (*metis prod.exhaust-sel*)
let *?eval-qs* = (*map* (*eval-mpoly-poly val*) *qs*)
have *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) =

(*let q1* = *take* ((*length ?eval-qs*) *div 2*) *?eval-qs*; *left* = *calculate-data-R ?eval-p q1*;
q2 = *drop* ((*length ?eval-qs*) *div 2*) *?eval-qs*; *right* = *calculate-data-R ?eval-p q2*;
comb = *combine-systems-R ?eval-p* (*q1*,*left*) (*q2*,*right*) *in*
reduce-system-R ?eval-p comb)
using *len-hyp*
by (*smt* (*z3*) *calculate-data-R.simps less-one nat-less-le semiring-norm*(*136*))

moreover have ... = (*let q1* =(*map* (*eval-mpoly-poly val*) *?q1*);
left = *calculate-data-R* (*eval-mpoly-poly val p*) *q1*;
q2 = (*map* (*eval-mpoly-poly val*) *?q2*);
right = *calculate-data-R* (*eval-mpoly-poly val p*) *q2*
in Let (*combine-systems-R* (*eval-mpoly-poly val p*) (*q1*, *left*) (*q2*, *right*))
(*reduce-system-R* (*eval-mpoly-poly val p*)))
using *map-q1 map-q2* **by** *auto*
moreover have ... = (*let q1* =(*map* (*eval-mpoly-poly val*) *?q1*); *left* = *me1*;
q2 = (*map* (*eval-mpoly-poly val*) *?q2*); *right* = *me2 in*

Let (*combine-systems-R* (*eval-mpoly-poly val p*) (*q1*, *left*) (*q2*, *right*))
(*reduce-system-R* (*eval-mpoly-poly val p*)))
unfolding *Let-def me1-ind me2-ind* **by** *auto*
moreover have ... = *mat-eq*
unfolding *Let-def reduce-mat-eq me-pre-var* **by** *auto*
ultimately have *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) = *mat-eq*
by *auto*
}
ultimately show *?case* **by** *blast*
qed

lemma *calculate-data-M-assumps-univariate*:
assumes *mat-eq*: (*assumps*, *mat-eq*) ∈ *set* (*calculate-data-assumps-M p qs init-assumps*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *p-nonzero*: *eval-mpoly-poly val p* ≠ *0*
shows *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) = *mat-eq*
using *assms*
proof (*induct length qs arbitrary*: *val p mat-eq assumps qs rule*: *less-induct*)
case (*less qs val p mat-eq assumps*)
have *length qs* = *0* ∨ *length qs* = *1* ∨ *length qs* > *1*
by (*meson less-one nat-neq-iff*)
moreover {assume ∗: *length qs* = *0*
let *?m* = (*mat-of-rows-list 3* [[*1*,*1*,*1*], [*0*,*1*,*0*], [*1*,*0*,−*1*]])
let *?subs* = [([], []),([*0*], []),([], [*0*])]
let *?signs* = [[*1*],[*0*],[−*1*]]
let *?eval-p* = *eval-mpoly-poly val p*
have *mat-eq-in*: (*assumps*, *mat-eq*) ∈ *set* (*calculate-data-assumps-M p* [] *init-assumps*)
using ∗ *less.prems*(*1*) **by** *auto*
let *?map-base* = *map* (λ(*assumps*,(*a*,(*b*,*c*))). (*assumps*, (*a*,*b*,*map* (*drop 1*) *c*)))
(*reduce-system-M p* [*1*] (*base-case-info-M-assumps init-assumps*))
have (*assumps*, *mat-eq*) ∈ *set ?map-base*
using *mat-eq-in*
by *auto*
then obtain *a1 b1 c1* **where** *a1b1c1-prop*:
(*assumps*, (*a1*, (*b1*, *c1*))) ∈ *set* (*reduce-system-M p* [*1*] (*base-case-info-M-assumps init-assumps*))
mat-eq = (*a1*, (*b1*, *map* (*drop 1*) *c1*))
by *auto*
have *base-case-well-def*: ⋀*in-a init-mat-eq Is1 Is2 n subs m signs*.
(*in-a*, *m*, *subs*, *signs*) ∈ *set* (*base-case-info-M-assumps init-assumps*) ⟹
(*Is1*, *Is2*) ∈ *set subs* ⟹ *n* ∈ *set Is1* ∨ *n* ∈ *set Is2* ⟹ *n* < *length* [*1*]
using *base-case-with-assumps-info-M-well-def*
by *auto*
have [*1*] = *map* (*eval-mpoly-poly val*) [*1*]
unfolding *eval-mpoly-poly-def eval-mpoly-def*
by *auto*
then have ∃ *acc mss*. (*acc*,*mss*) ∈ *set* ((*base-case-info-M-assumps init-assumps*))

$\wedge$ (*a1*, (*b1*, *c1*)) = *reduce-system-R* (*eval-mpoly-poly val p*) ([*1*],*mss*)
using *reduce-system-M-univariate*[*of assumps* (*a1*, *b1*, *c1*) *p* [*1*] (*base-case-info-M-assumps init-assumps*) *val* [*1*]]
a1b1c1-prop less(*3*) *base-case-well-def* **apply** (*auto*)
by *metis*
then obtain *acc mss* **where** *a1b1c1-connect*:
(*acc*,*mss*) $\in$ *set* ((*base-case-info-M-assumps init-assumps*))
(*a1*, (*b1*, *c1*)) = *reduce-system-R* (*eval-mpoly-poly val p*) ([*1*],*mss*)
by *auto*
then have *mss-is*: *mss* = *base-case-info-R*
unfolding *base-case-info-M-assumps-def*
using *Renegar-Algorithm.base-case-info-R-def Renegar-Algorithm.base-case-info-R-def*
by *auto*
obtain *a b c* **where** *abc-prop*: (*a*, *b*, *c*) = *reduction-step-R ?m ?signs ?subs* (*solve-for-lhs-R ?eval-p* [*1*] *?subs ?m*)
by (*metis reduction-step-R.simps*)
then have (*a*, *b*, *c*) = (*a1*, *b1*, *c1*)
using *abc-prop a1b1c1-prop*
by (*metis a1b1c1-connect*(*2*) *base-case-info-R-def mss-is reduce-system-R.simps*)

then have *mat-eq-is*: (*a*, *b*, *map* (*drop* (*Suc 0*)) *c*) = *mat-eq*
using *a1b1c1-prop*(*2*) **by** (*auto*)
have (*a*, *b*, *c*) =
reduction-step-R (*mat-of-rows-list 3* [[*1*, *1*, *1*], [*0*, *1*, *0*], [*1*, *0*, − *1*]])
[[*1*], [*0*], [− *1*]] [([], []), ([*0*], []), ([], [*0*])]
(*solve-for-lhs-R* (*eval-mpoly-poly val p*) [*1*]
[([], []), ([*0*], []), ([], [*0*])]
(*mat-of-rows-list 3* [[*1*, *1*, *1*], [*0*, *1*, *0*], [*1*, *0*, − *1*]]))
using *abc-prop*
unfolding *base-case-info-R-def*
by (*smt* (*verit*) *old.prod.case reduce-system-R.simps*)
then have *calculate-data-R ?eval-p* (*map* (*eval-mpoly-poly val*) *qs*)= *mat-eq*
using *mat-eq-is* $*$
by (*smt* (*z3*) *a1b1c1-connect*(*2*) *a1b1c1-prop*(*2*) *calculate-data-R.simps length-map mss-is split-conv*)
}
moreover {assume $*$: *length qs* = *1*
have *meq*: (*assumps*, *mat-eq*) $\in$ *set* (*reduce-system-M p qs* (*base-case-info-M-assumps init-assumps*))
using $*$ *le-eq-less-or-eq less*(*2*) *one-neq-zero* **by** *auto*
have $**$: $\bigwedge$*init-assumps init-mat-eq Is1 Is2 n subs m signs*.
(*init-assumps*, *m*, *subs*, *signs*) $\in$ *set* (*base-case-info-M-assumps init-assumps*)
$\Longrightarrow$
(*Is1*, *Is2*) $\in$ *set subs* $\Longrightarrow$
n $\in$ *set Is1* $\vee$ *n* $\in$ *set Is2* $\Longrightarrow$
n < *length qs* **unfolding** $*$
using *base-case-with-assumps-info-M-well-def*
by *meson*
from *reduce-system-M-univariate*[*OF meq less*(*3*), *of map* (*eval-mpoly-poly val*)

qs]
obtain *acc mss* **where** *ams*: (*acc*,*mss*) ∈ *set* (*base-case-info-M-assumps init-assumps*)

mat-eq = *reduce-system-R* (*eval-mpoly-poly val p*)
(*map* (*eval-mpoly-poly val*) *qs*, *mss*)
using ∗∗
apply (*auto*)
by (*smt* (*z3*) ∗ *base-case-with-assumps-info-M-well-def*)
then have *mss* = *base-case-info-R* **unfolding** *base-case-info-M-assumps-def*
using *Renegar-Algorithm.base-case-info-R-def Renegar-Algorithm.base-case-info-R-def*
by *auto*
then have *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) = *mat-eq*
using *ams* ∗ **by** *simp*
}

moreover {assume ∗: *length qs* > *1*
have *inset*: (*assumps*, *mat-eq*) ∈ *set* (*calculate-data-assumps-M p qs init-assumps*)
using *less.prems*(*1*)
by *auto*
let *?len* = *length qs*
let *?q1* = *take* (*?len div 2*) *qs*
let *?q2* = *drop* (*?len div 2*) *qs*
let *?left* = *calculate-data-assumps-M p ?q1 init-assumps*
let *?right* = *calculate-data-assumps-M p ?q2 init-assumps*
let *?comb* = *combine-systems-M p ?q1 ?left ?q2 ?right*
let *?eval-p* = (*eval-mpoly-poly val p*)
let *?eval-q1* = (*map* (*eval-mpoly-poly val*) *?q1*)
let *?eval-q2* = (*map* (*eval-mpoly-poly val*) *?q2*)
have *map-q1*: *map* (*eval-mpoly-poly val*) *?q1* =
(*take* (*length* (*map* (*eval-mpoly-poly val*) *qs*) *div 2*) (*map* (*eval-mpoly-poly val*) *qs*))
by (*auto simp add*: *take-map*)
have *map-q2*: *map* (*eval-mpoly-poly val*) *?q2* =
(*drop* (*length* (*map* (*eval-mpoly-poly val*) *qs*) *div 2*) (*map* (*eval-mpoly-poly val*) *qs*))
by (*auto simp add*: *drop-map*)
have *fst ?comb* = *qs*
by *auto*
then have (*assumps*, *mat-eq*) ∈ *set* (*reduce-system-M p qs* (*snd ?comb*))
using *inset* ∗
by (*smt* (*z3*) *calculate-data-assumps-M.simps gr-implies-not0 less-one nat-less-le*)

then have (*assumps*, *mat-eq*) ∈ *set* (*concat* (*map* (*reduce-system-single-M p qs*) (*snd ?comb*)))
by (*metis reduce-system-M.simps*)
then have ∃ *sys*. *sys* ∈ *set* (*snd ?comb*) ∧ (*assumps*, *mat-eq*) ∈ *set*(*reduce-system-single-M p qs sys*)
using *concat-map-in-set*

by (*metis nth-mem*)
then obtain *a-pre me-pre* **where** *reduce-prop*: (*a-pre*, *me-pre*) ∈ *set* (*snd ?comb*)
(*assumps*, *mat-eq*) ∈ *set*(*reduce-system-single-M p qs* (*a-pre*, *me-pre*))
by *fastforce*
then obtain *a1 me1 a2 me2* **where** *mes-prop*: (*a1*, *me1*) ∈ *set ?left*
(*a2*, *me2*) ∈ *set ?right*
(*a-pre*, *me-pre*) = *combine-systems-single-M p ?q1* (*a1*, *me1*) *?q2* (*a2*, *me2*)
by *auto*
then have *a-pre*: *a-pre* = *a1*@*a2*
by *auto*
have *lengt*: *length qs div 2* ≥ *1*
using ∗ **by** *auto*
then have *len-q1*: *length ?q1* < *length qs*
by *auto*
have *len-q2*: *length ?q2* < *length qs*
using *lengt* **by** *auto*
obtain *mat-pre subs-pre signs-pre* **where** *me-decomp*:
me-pre = (*mat-pre*,*subs-pre*,*signs-pre*)
using *mes-prop*
using *prod-cases3* **by** *blast*
then have *assumps* ∈ *set* (*map fst* (*solve-for-lhs-M p a-pre qs subs-pre mat-pre*))
using *reduce-prop*(*2*) **by** *auto*
then have *assumps* ∈ *set* (*map fst* (*construct-rhs-vector-M p a-pre qs subs-pre*))
unfolding *solve-for-lhs-M-def* **by** *auto*
then obtain *a-rhs-list* **where** (*assumps*, *a-rhs-list*)
∈ *set* (*construct-rhs-vector-rec-M p a-pre* (*pull-out-pairs qs subs-pre*))
unfolding *construct-rhs-vector-M-def* **by** *auto*
then have *a-pre-subset*: *set a-pre* ⊆ *set assumps*
using *construct-rhs-vector-rec-M-subset-prop*[*of assumps - p a-pre* (*pull-out-pairs qs subs-pre*)]
by *auto*
have *set-a1*: *set a1* ⊆ *set assumps*
using *a-pre-subset a-pre* **by** *auto*
then have *a1-satisfies*: (⋀*p n*. (*p*, *n*) ∈ *set a1* ⟹ *satisfies-evaluation val p n*)
using *less*(*3*) **by** *blast*
from *less.hyps*[*of ?q1 a1 me1*, *OF len-q1 mes-prop*(*1*) *a1-satisfies*]
have *me1-ind*: *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *?q1*) = *me1*
using *less*(*4*) **by** *blast*
have *set-a2*: *set a2* ⊆ *set assumps*
using *a-pre-subset a-pre* **by** *auto*
then have *a2-satisfies*: (⋀*p n*. (*p*, *n*) ∈ *set a2* ⟹ *satisfies-evaluation val p n*)
using *less*(*3*) **by** *blast*
from *less.hyps*[*of ?q2 a2 me2*, *OF len-q2 mes-prop*(*2*) *a2-satisfies*]
have *me2-ind*: *calculate-data-R ?eval-p* (*map* (*eval-mpoly-poly val*) *?q2*) = *me2*
using *less*(*4*) **by** *blast*
have *me-pre*: *me-pre* = *snd* (*combine-systems-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *?q1*), *me1*) ((*map* (*eval-mpoly-poly val*) *?q2*), *me2*))

using *mes-prop(3) combine-systems-R-snd length-map*
by (*metis combine-systems-single-M.simps snd-conv*)
obtain *mat-pre1 subs-pre1 signs-pre1* **where** *me1-decomp*:
me1 = (*mat-pre1*,*subs-pre1*,*signs-pre1*)
using *prod-cases3* **by** *blast*
obtain *mat-pre2 subs-pre2 signs-pre2* **where** *me2-decomp*:
me2 = (*mat-pre2*,*subs-pre2*,*signs-pre2*)
using *prod-cases3* **by** *blast*
have *fst-comb*: *fst* (*combine-systems-R ?eval-p* ((*map* (*eval-mpoly-poly val*) *?q1*), *me1*) ((*map* (*eval-mpoly-poly val*) *?q2*), *me2*)) = (*map* (*eval-mpoly-poly val*) *?q1*) @ (*map* (*eval-mpoly-poly val*) *?q2*)
proof −
have *fst* (*combine-systems-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *?q1*), *me1*) ((*map* (*eval-mpoly-poly val*) *?q2*), *me2*)) =
fst (*smash-systems-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *?q1*) (*map* (*eval-mpoly-poly val*) *?q2*) *subs-pre1 subs-pre2 signs-pre1 signs-pre2 mat-pre1 mat-pre2*)
using *combining-to-smash-R me1-decomp me2-decomp* **by** *force*
then show *?thesis*
unfolding *smash-systems-R-def* **by** *auto*
qed
then have *map* (*eval-mpoly-poly val*) *qs* = *fst* (*combine-systems-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *?q1*), *me1*) ((*map* (*eval-mpoly-poly val*) *?q2*), *me2*))
by (*metis append-take-drop-id map-append*)
then have *me-pre-var*: (*map* (*eval-mpoly-poly val*) *qs*, *me-pre*) = (*combine-systems-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *?q1*), *me1*) ((*map* (*eval-mpoly-poly val*) *?q2*), *me2*))
using *me-pre* **by** *auto*
have *len-hyp*: *length* (*map* (*eval-mpoly-poly val*) *qs*) > *1*
using ∗ **by** *auto*
have *len-eq*: *length* (*map* (*eval-mpoly-poly val*) *qs*) = *length qs*
by *simp*
have *len-q1-gt0*: *length* (*map* (*eval-mpoly-poly val*) *?q1*) > *0*
using *len-hyp len-eq* **by** *auto*
have *len-q2-gt0*: *length* (*map* (*eval-mpoly-poly val*) *?q2*) > *0*
using *len-hyp len-eq* **by** *auto*
let *?uni-sys-q1* = *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *?q1*)
have *sat-props-q1-univ*: *satisfies-properties-R ?eval-p* (*map* (*eval-mpoly-poly val*) *?q1*) (*get-subsets-R ?uni-sys-q1*) (*get-signs-R ?uni-sys-q1*) (*get-matrix-R ?uni-sys-q1*)
using *calculate-data-satisfies-properties-R*[*of ?eval-p* (*map* (*eval-mpoly-poly val*) (*take* (*length qs div 2*) *qs*))]
len-q1-gt0 **using** *less.prems*(*3*) **by** *auto*
let *?uni-sys-q2* = *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *?q2*)
have *sat-props-q2-univ*: *satisfies-properties-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *?q2*) (*get-subsets-R ?uni-sys-q2*) (*get-signs-R ?uni-sys-q2*) (*get-matrix-R ?uni-sys-q2*)

using *calculate-data-satisfies-properties-R*[*of* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) (*drop* (*length qs div 2*) *qs*))]
len-q2-gt0 **using** *less.prems*(*3*) **by** *auto*
have *comb-satisfies*: *satisfies-properties-R ?eval-p* (*?eval-q1*@(*map* (*eval-mpoly-poly val*) *?q2*))
(*get-subsets-R* (*snd* ((*combine-systems-R ?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))))

(*get-signs-R* (*snd* ((*combine-systems-R ?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))))

(*get-matrix-R* (*snd* ((*combine-systems-R ?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))))
using *combining-sys-satisfies-properties-R*[*of ?eval-p ?eval-q1 ?eval-q2*] *len-q1-gt0* *len-q2-gt0 less.prems*(*3*)
sat-props-q2-univ sat-props-q1-univ
by *auto*
then have *well-def-subs-pre*: *all-list-constr-R* (*get-subsets-R* (*snd* ((*combine-systems-R* *?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))) (*length* (*?eval-q1*@*?eval-q2*))
unfolding *satisfies-properties-R-def* **by** *auto*
have *get-subs-pre*: (*get-subsets-R* (*snd* ((*combine-systems-R ?eval-p* (*?eval-q1*,*?uni-sys-q1*) (*?eval-q2*,*?uni-sys-q2*)))) = *subs-pre*
using *me-decomp* **unfolding** *get-subsets-R-def*
by (*metis fst-conv me1-ind me2-ind me-pre-var snd-conv*)
have *well-def*: (⋀*Is1 Is2 n*. (*Is1*, *Is2*) ∈ *set* (*fst* (*snd me-pre*)) ⟹ *n* ∈ *set Is1* ∨ *n* ∈ *set Is2* ⟹ *n* < *length qs*)
using *well-def-subs-pre get-subs-pre*
all-list-constr-R-matches-well-def[*of subs-pre*]
by (*smt* (*verit*, *ccfv-SIG*) *fst-comb fst-conv get-subsets-R-def length-map me1-ind me2-ind me-pre-var snd-conv*)
then have *reduce-mat-eq*: *mat-eq* = *reduce-system-R* (*eval-mpoly-poly val p*) ((*map* (*eval-mpoly-poly val*) *qs*), *me-pre*)
using *reduce-system-single-M-univariate*[*OF reduce-prop*(*2*) *less.prems*(*2*)]
by (*metis prod.exhaust-sel*)
let *?eval-qs* = (*map* (*eval-mpoly-poly val*) *qs*)
have *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) =

(*let q1* = *take* ((*length ?eval-qs*) *div 2*) *?eval-qs*; *left* = *calculate-data-R ?eval-p q1*;
q2 = *drop* ((*length ?eval-qs*) *div 2*) *?eval-qs*; *right* = *calculate-data-R ?eval-p q2*;
comb = *combine-systems-R ?eval-p* (*q1*,*left*) (*q2*,*right*) *in*
reduce-system-R ?eval-p comb)
using *len-hyp*
by (*smt* (*z3*) *calculate-data-R.simps less-one nat-less-le semiring-norm*(*136*))

moreover have ... = (*let q1* =(*map* (*eval-mpoly-poly val*) *?q1*);
left = *calculate-data-R* (*eval-mpoly-poly val p*) *q1*;
q2 = (*map* (*eval-mpoly-poly val*) *?q2*);
right = *calculate-data-R* (*eval-mpoly-poly val p*) *q2*
in Let (*combine-systems-R* (*eval-mpoly-poly val p*) (*q1*, *left*) (*q2*, *right*))
(*reduce-system-R* (*eval-mpoly-poly val p*)))

using *map-q1 map-q2* **by** *auto*
moreover have ... = (*let q1* =(*map* (*eval-mpoly-poly val*) *?q1*); *left* = *me1*;
q2 = (*map* (*eval-mpoly-poly val*) *?q2*); *right* = *me2 in*
Let (*combine-systems-R* (*eval-mpoly-poly val p*) (*q1*, *left*) (*q2*, *right*))
(*reduce-system-R* (*eval-mpoly-poly val p*)))
unfolding *Let-def me1-ind me2-ind* **by** *auto*
moreover have ... = *mat-eq*
unfolding *Let-def reduce-mat-eq me-pre-var* **by** *auto*
ultimately have *calculate-data-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*) = *mat-eq*
by *auto*
}
ultimately show *?case* **by** *blast*
qed

lemma *calculate-data-gives-signs-at-roots*:
assumes (*assumps*, *signs*) ∈ *set* (*calculate-data-to-signs* (*calculate-data-M p qs*))
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *eval-mpoly-poly val p* ≠ *0*
shows *signs* = *find-consistent-signs-at-roots-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*)
using *assms calculate-data-M-univariate*
unfolding *find-consistent-signs-at-roots-R-def* **by** *auto*

lemma *calculate-data-gives-noncomp-signs-at-roots*:
assumes (*assumps*, *signs*) ∈ *set* (*calculate-data-to-signs* (*calculate-data-M p qs*))
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *eval-mpoly-poly val p* ≠ *0*
shows *set signs* = *set* (*characterize-consistent-signs-at-roots* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*))
using *assms find-consistent-signs-at-roots-R calculate-data-gives-signs-at-roots*
by *metis*

lemma *calculate-data-assumps-gives-signs-at-roots*:
assumes (*assumps*, *signs*) ∈ *set* (*calculate-data-to-signs* (*calculate-data-assumps-M p qs init-assumps*))
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *eval-mpoly-poly val p* ≠ *0*
shows *signs* = *find-consistent-signs-at-roots-R* (*eval-mpoly-poly val p*) (*map* (*eval-mpoly-poly val*) *qs*)
using *assms calculate-data-M-assumps-univariate*
unfolding *find-consistent-signs-at-roots-R-def*
by *auto*

lemma *calculate-data-assumps-gives-noncomp-signs-at-roots*:
assumes (*assumps*, *signs*) ∈ *set* (*calculate-data-to-signs* (*calculate-data-assumps-M p qs init-assumps*))
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
assumes *eval-mpoly-poly val p* ≠ *0*

shows *set signs = set (characterize-consistent-signs-at-roots (eval-mpoly-poly val p) (map (eval-mpoly-poly val) qs))*
using *assms find-consistent-signs-at-roots-R calculate-data-assumps-gives-signs-at-roots*
by *metis*

end

theory *Hybrid-Multiv-Algorithm-Proofs*

imports *Hybrid-Multiv-Algorithm*
Hybrid-Multiv-Matrix-Proofs
Virtual-Substitution.ExportProofs

begin

17.8 Lemmas about branching (lc assump generation)

lemma *lc-assump-generation-induct*[*case-names Base Rec Lookup0 LookupN0*]:
fixes *q* :: *real mpoly Polynomial.poly*
fixes *assumps* ::(*real mpoly* × *rat*) *list*
assumes *base*: ⋀*q assumps*. *q* = *0* ⟹ *P q assumps*
and *rec*: ⋀*q assumps*.
⟦*q* ≠ *0*;
lookup-assump-aux (*Polynomial.lead-coeff q*) *assumps* = *None*;
P (*one-less-degree q*) ((*Polynomial.lead-coeff q*, *0*) # *assumps*)⟧ ⟹
P q assumps
and *lookup0*: ⋀*q assumps*.
⟦*q* ≠ *0*;
lookup-assump-aux (*Polynomial.lead-coeff q*) *assumps* = *Some 0*;
P (*one-less-degree q*) *assumps*⟧ ⟹ *P q assumps*
and *lookupN0*: ⋀*q assumps r*.
⟦*q* ≠ *0*;
lookup-assump-aux (*Polynomial.lead-coeff q*) *assumps* = *Some r*;
r ≠ *0*⟧ ⟹ *P q assumps*
shows *P q assumps*
apply(*induct q assumps rule*: *lc-assump-generation.induct*)
by (*metis base rec lookup0 lookupN0 not-None-eq*)

lemma *lc-assump-generation-subset*:
assumes (*branch-assms*, *branch-poly-list*) ∈ *set*(*lc-assump-generation q assumps*)
shows *set assumps* ⊆ *set branch-assms*
using *assms*
proof (*induct q assumps rule*: *lc-assump-generation-induct*)
case (*Base q assumps*)
then show *?case*
by (*auto simp add*: *lc-assump-generation.simps*)

next
case (*Rec q assumps*)
let *?zero* = *lc-assump-generation* (*one-less-degree q*) ((*Polynomial.lead-coeff q*, (*0*::*rat*)) # *assumps*)
let *?one* = ((*Polynomial.lead-coeff q*, (*1*::*rat*)) # *assumps*, *q*)
let *?minus-one* = ((*Polynomial.lead-coeff q*, (−*1*::*rat*)) # *assumps*, *q*)
have (*branch-assms*, *branch-poly-list*) ∈ *set* (*?one*#*?minus-one*#*?zero*)
using *Rec.hyps Rec*(*4*) *lc-assump-generation.simps* **by** *auto*
then show *?case*
using *Rec*(*3*) **by** *force*
next
case (*Lookup0 q assumps*)
then show *?case*
using *lc-assump-generation.simps*
by *simp*
next
case (*LookupN0 q assumps r*)
then show *?case*
by (*auto simp add*: *lc-assump-generation.simps*)
qed

lemma *branch-init-assms-subset*:
assumes (*branch-assms*, *branch-poly-list*) ∈ *set* (*lc-assump-generation-list qs init-assumps*)
shows *set init-assumps* ⊆ *set branch-assms*
using *assms*
proof (*induct qs arbitrary*: *branch-assms branch-poly-list init-assumps*)
case *Nil*
then show *?case*
by (*simp add*: *lc-assump-generation-list.simps*(*1*))
next
case (*Cons a bpl*)
then show *?case*
using *lc-assump-generation-subset*
apply (*auto simp add*: *lc-assump-generation-list.simps*)
by *blast*
qed

lemma *prod-list-var-gen-nonzero*:
shows *prod-list-var-gen qs* ≠ *0*
proof (*induct qs*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a qs*)
then show *?case* **by** *auto*
qed

lemma *lc-assump-generation-inv*:
assumes $(a, q) \in set\ (lc\text{-}assump\text{-}generation\ init\text{-}q\ assumps)$
shows $q = (0::rmpoly) \vee (\exists i.\ (lookup\text{-}assump\text{-}aux\ (Polynomial.lead\text{-}coeff\ q)\ a = Some\ i \wedge i \neq 0))$
using *assms*
proof (*induct init-q assumps arbitrary*: *q a rule*: *lc-assump-generation-induct*)
case (*Base init-q assumps*)
then show *?case*
using *lc-assump-generation.simps* **by** *auto*
next
case (*Rec init-q assumps*)
let *?zero* = *lc-assump-generation* (*one-less-degree init-q*) ((*Polynomial.lead-coeff init-q*, (*0*::*rat*)) # *assumps*)
let *?one* = ((*Polynomial.lead-coeff init-q*, (*1*::*rat*)) # *assumps*, *init-q*)
let *?minus-one* = ((*Polynomial.lead-coeff init-q*, (*−1*::*rat*)) # *assumps*, *init-q*)
have $(a, q) \in set\ (?one\ \#\ ?minus\text{-}one\ \#\ ?zero)$
using *Rec.prems Rec.hyps*(*1*) *Rec.hyps*(*2*) *lc-assump-generation.simps*
by *auto*
then have *eo*: $(a, q) = ?one \vee (a, q) = ?minus\text{-}one \vee (a, q) \in set(?zero)$
by *auto*
{assume ∗: $(a, q) = ?one$
then have $q = (0::rmpoly) \vee (\exists i.\ (lookup\text{-}assump\text{-}aux\ (Polynomial.lead\text{-}coeff\ q)\ a = Some\ i \wedge i \neq 0))$
by *auto*
}
moreover {assume ∗: $(a, q) = ?minus\text{-}one$
then have $q = (0::rmpoly) \vee (\exists i.\ (lookup\text{-}assump\text{-}aux\ (Polynomial.lead\text{-}coeff\ q)\ a = Some\ i \wedge i \neq 0))$
by *auto*
}
moreover {assume ∗: $(a, q) \in set(?zero)$
then have $q = (0::rmpoly) \vee (\exists i.\ (lookup\text{-}assump\text{-}aux\ (Polynomial.lead\text{-}coeff\ q)\ a = Some\ i \wedge i \neq 0))$
using *Rec.hyps Rec.prems* **by** *auto*
}
ultimately show *?case*
using *lc-assump-generation.simps*
using *eo* **by** *fastforce*
next
case (*Lookup0 init-q assumps*)
then show *?case* **using** *lc-assump-generation.simps* **by** *auto*
next
case (*LookupN0 init-q assumps r*)
then show *?case* **using** *lc-assump-generation.simps* **by** *auto*
qed

lemma *lc-assump-generation-list-inv*:
assumes *val*: $\bigwedge p\ n.\ (p,n) \in set\ branch\text{-}assms \Longrightarrow satisfies\text{-}evaluation\ val\ p\ n$
assumes $(branch\text{-}assms,\ branch\text{-}poly\text{-}list) \in set\ (lc\text{-}assump\text{-}generation\text{-}list\ qs$

init-assumps)
shows $q \in$ *set branch-poly-list* $\Longrightarrow$ $q = 0 \vee (\exists\, i.$ *lookup-assump-aux* (*Polynomial.lead-coeff* q) *branch-assms* = *Some* $i \wedge i \neq 0$)
using *assms*
proof (*induct qs arbitrary*: q *init-assumps branch-poly-list branch-assms*)
case *Nil*
then have (*branch-assms*, *branch-poly-list*) $\in$ *set* [(*init-assumps*, [])]
using *lc-assump-generation-list.simps* **by** *auto*
then have *branch-poly-list* = []
by *simp*
then show *?case*
using *Nil.prems*(*1*)
by *simp*
next
case (*Cons a qs*)
let *?rec* = *lc-assump-generation a init-assumps*
have *inset*: (*branch-assms*,*branch-poly-list*) $\in$ *set* (
concat (*map* (
λ(*new-assumps*, *r*). (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)) *?rec*))
using *Cons.prems lc-assump-generation-list.simps*
by *auto*
then obtain *new-assumps r* **where** *deconstruct-prop*:
(*new-assumps*, *r*) $\in$ *set ?rec*
(*branch-assms*,*branch-poly-list*) $\in$ *set* (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)
using *inset*
by (*metis* (*no-types*, *lifting*) *concat-map-in-set nth-mem prod.collapse split-def*)
then obtain *elem list-rec* **where** *list-rec-prop*:
list-rec = *lc-assump-generation-list qs new-assumps*
elem $\in$ *set list-rec*
(*branch-assms*,*branch-poly-list*) = (*fst elem*, *r*#(*snd elem*))
by *auto*
then have *pair-in-set*: (*branch-assms*, *snd elem*) $\in$ *set* (*lc-assump-generation-list qs new-assumps*)
using *deconstruct-prop* **by** *auto*
then have *snd-elem-is*: $\bigwedge q.$ $q \in$ *set* (*snd elem*) $\Longrightarrow$
$q = 0 \vee (\exists\, i.$ *lookup-assump-aux* (*Polynomial.lead-coeff* q) *branch-assms* = *Some* $i \wedge i \neq 0$)
using *Cons.hyps*
by (*simp add*: *local.Cons*(*3*))
have *ris-var*: $r = 0 \vee (\exists\, i.$ *lookup-assump-aux* (*Polynomial.lead-coeff r*)*new-assumps* = *Some* $i \wedge i \neq 0$)
using *lc-assump-generation-inv*[*of new-assumps r a init-assumps*] *deconstruct-prop*(*1*)

by *auto*
have *set new-assumps* $\subseteq$ *set branch-assms*
using *deconstruct-prop list-rec-prop*

using *pair-in-set branch-init-assms-subset* **by** *presburger*
then have (∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff r*) *new-assumps* = *Some i* ∧ *i* ≠ *0*) ⟹
(∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff r*) *branch-assms* = *Some i* ∧ *i* ≠ *0*)
using *val lookup-assump-aux-subset-consistency*
using *local.Cons*(*3*) **by** *blast*
then have *ris*: *r* = *0* ∨ (∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff r*) *branch-assms* = *Some i* ∧ *i* ≠ *0*)
using *ris-var* **by** *auto*
then show *?case*
using *ris snd-elem-is list-rec-prop*(*3*)
using *Cons.prems*(*1*) **by** *auto*
qed

17.9 Correctness of sign determination inner

lemma *q-dvd-prod-list-var-prop*:
assumes *q* ∈ *set qs*
assumes *q* ≠ *0*
shows *q dvd prod-list-var-gen qs* **using** *assms*
proof (*induct qs*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a qs*)
then have *eo*: *q* = *a* ∨*q* ∈ *set qs* **by** *auto*
have *c1*: *q* = *a* ⟹ *q dvd prod-list-var-gen* (*a*#*qs*)
proof −
assume *q* = *a*
then have *prod-list-var-gen* (*a*#*qs*) = *q*∗(*prod-list-var-gen qs*) **using** *Cons.prems*
unfolding *prod-list-var-gen-def* **by** *auto*
then show *?thesis* **using** *prod-list-var-gen-nonzero*[*of qs*] **by** *auto*
qed
have *c2*: *q* ∈ *set qs* ⟶ *q dvd prod-list-var-gen qs*
using *Cons.prems Cons.hyps* **unfolding** *prod-list-var-gen-def* **by** *auto*
show *?case* **using** *eo c1 c2* **by** *auto*
qed

lemma *poly-p-nonzero-on-branch*:
assumes *assms*: ⋀*p n*. (*p*,*n*) ∈ *set branch-assms* ⟹ *satisfies-evaluation val p n*
assumes (*branch-assms*, *branch-poly-list*) ∈ *set* (*lc-assump-generation-list qs init-assumps*)
assumes *p* = *poly-p-in-branch* (*branch-assms*, *branch-poly-list*)
shows *eval-mpoly-poly val p* ≠ *0*
proof −

{assume ∗: (*check-all-const-deg-gen branch-poly-list* = *True*)
then have *p-is*: *p* = [:*0*, *1*:]

```
      using assms
      using poly-p-in-branch.simps by presburger
    then have eval-mpoly-poly val p ≠ 0
    by (metis Polynomial.lead-coeff-monom degree-0 dvd-refl eval-commutes eval-mpoly-map-poly-comm-ring-ho
not-is-unit-0 poly-dvd-1 x-as-monom)
  }
  moreover {assume ∗: (check-all-const-deg-gen branch-poly-list = False)
   then have p-is: p = (pderiv (prod-list-var-gen branch-poly-list)) ∗ (prod-list-var-gen
branch-poly-list)
      using assms
      using poly-p-in-branch.simps by presburger
   then have assms-inv: ⋀q. q ∈ set branch-poly-list ⟹ q = 0 ∨ (∃ i. lookup-assump-aux
(Polynomial.lead-coeff q) branch-assms = Some i ∧ i ≠ 0)
      using lc-assump-generation-list-inv assms
      by (meson assms(2))
    have q-inv: ⋀q. q ∈ set branch-poly-list ⟹ q ≠ 0 ⟹ eval-mpoly-poly val q
≠ 0
      using assms-inv assms
        by (metis eval-commutes leading-coeff-0-iff lookup-assum-aux-mem satis-
fies-evaluation-nonzero)
    then have ⋀q. q ∈ set branch-poly-list ⟹ (q ≠ 0 ⟷ eval-mpoly-poly val q
≠ 0)
      by auto
   then have prod-list-eval: (eval-mpoly-poly val (prod-list-var-gen branch-poly-list))
= (prod-list-var-gen (map (eval-mpoly-poly val) branch-poly-list))
    proof (induct branch-poly-list)
      case Nil
      then show ?case by auto
    next
      case (Cons a branch-poly-list)
      { assume ∗: a = 0
       then have h1: eval-mpoly-poly val (prod-list-var-gen (a # branch-poly-list))
=
          eval-mpoly-poly val (prod-list-var-gen branch-poly-list)
          by simp
        have eval-mpoly-poly val a = 0
          using ∗ by auto
      then have h2: prod-list-var-gen (map (eval-mpoly-poly val) (a # branch-poly-list))
      = prod-list-var-gen (map (eval-mpoly-poly val) branch-poly-list)
          by auto
        then have eval-mpoly-poly val (prod-list-var-gen (a # branch-poly-list)) =
       prod-list-var-gen (map (eval-mpoly-poly val) (a # branch-poly-list))
          using Cons.hyps Cons.prems h1 h2
          by simp
      }
      moreover { assume ∗: a ≠ 0
       then have h1: eval-mpoly-poly val (prod-list-var-gen (a # branch-poly-list))
=
       (eval-mpoly-poly val a)∗(eval-mpoly-poly val (prod-list-var-gen branch-poly-list))
```

by (*simp add*: *eval-mpoly-poly-comm-ring-hom.hom-mult*)
have *eval-mpoly-poly val a* ≠ *0*
using ∗ *assms Cons.prems*
by (*meson list.set-intros*(*1*))
then have *h2*: *prod-list-var-gen* (*map* (*eval-mpoly-poly val*) (*a* # *branch-poly-list*))
= (*eval-mpoly-poly val a*)∗ *prod-list-var-gen* (*map* (*eval-mpoly-poly val*) *branch-poly-list*)
by *auto*
have *eval-mpoly-poly val* (*prod-list-var-gen* (*a* # *branch-poly-list*)) =
prod-list-var-gen (*map* (*eval-mpoly-poly val*) (*a* # *branch-poly-list*))
using *Cons.hyps Cons.prems h1 h2*
by *simp*
}
ultimately show *?case*
by *auto*
qed
have *degree-q-inv*: ⋀*q*. *q* ∈ *set branch-poly-list* ⟹ *q* ≠ *0* ⟹ *Polynomial.degree* (*eval-mpoly-poly val q*) = *Polynomial.degree q*
using *assms-inv assms q-inv*
by (*metis degree-valuation lookup-assum-aux-mem*)
have *prod-nonz*: *eval-mpoly-poly val* (*prod-list-var-gen branch-poly-list*) ≠ *0*
using *q-inv prod-list-eval*
by (*simp add*: *prod-list-var-gen-nonzero*)
have *ex-q*: ∃ *q* ∈ *set branch-poly-list*. (*q* ≠ *0* ∧ *Polynomial.degree q* > *0*)
using ∗ **proof** (*induct branch-poly-list*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a branch-poly-list*)
then show *?case*
by (*metis bot-nat-0.not-eq-extremum check-all-const-deg-gen.simps*(*2*) *degree-0 list.set-intros*(*1*) *list.set-intros*(*2*))
qed
obtain *pos-deg-poly* **where** *pos-deg-poly*: *pos-deg-poly*∈*set branch-poly-list* ∧ *pos-deg-poly* ≠ *0* ∧ *0* < *Polynomial.degree pos-deg-poly*
using *ex-q* **by** *blast*
have *pos-deg-poly dvd* (*prod-list-var-gen branch-poly-list*)
by (*simp add*: *Hybrid-Multiv-Algorithm-Proofs.q-dvd-prod-list-var-prop pos-deg-poly*)
then have *nonc-dvd*: (*eval-mpoly-poly val pos-deg-poly*) *dvd* (*eval-mpoly-poly val* (*prod-list-var-gen branch-poly-list*))
by *blast*
have *Polynomial.degree* (*eval-mpoly-poly val pos-deg-poly*) > *0*
using *pos-deg-poly degree-q-inv*
by *metis*
then have *prod-nonc*:*Polynomial.degree* (*eval-mpoly-poly val* (*prod-list-var-gen branch-poly-list*)) ≠ *0*
using *nonc-dvd prod-nonz*
by (*metis bot-nat-0.extremum-strict dvd-const*)
then have *eval-mpoly-poly val p* ≠ *0*

```
    using prod-nonz prod-nonc
      by (metis eval-mpoly-poly-comm-ring-hom.hom-mult no-zero-divisors p-is
pderiv-commutes pderiv-eq-0-iff)
  }
  ultimately show ?thesis by auto
qed

lemma calc-data-to-signs-and-extract-signs:
  shows (calculate-data-to-signs ell) = extract-signs ell
  by auto

lemma branch-poly-eval:
  assumes (a, q) ∈ set (lc-assump-generation init-q init-assumps)
  assumes ⋀p n. (p, n) ∈ set a ⟹ satisfies-evaluation val p n
  shows eval-mpoly-poly val q = eval-mpoly-poly val init-q
  using assms
proof (induct init-q init-assumps arbitrary: q a rule: lc-assump-generation-induct)
  case (Base init-q init-assumps)
  then show ?case
    by (simp add: lc-assump-generation.simps)
next
  case (Rec init-q init-assumps)
  from Rec.prems(1) Rec.hyps(1−2) Rec.prems(2) Rec.hyps(3) [of a q]
  show ?case
    using eval-mpoly-poly-one-less-degree [of val init-q]
     lc-assump-generation-subset [of a q ‹one-less-degree init-q› ‹(Polynomial.lead-coeff
init-q, 0) # init-assumps›] lc-assump-generation.simps [of init-q init-assumps]
    by auto
next
  case (Lookup0 init-q init-assumps)
  then show ?case
    using lc-assump-generation.simps
   by (smt (z3) eval-mpoly-poly-one-less-degree lc-assump-generation-subset lookup-assum-aux-mem
option.simps(5) subset-eq)

next
  case (LookupN0 init-q init-assumps r)
  then show ?case
    by (simp add: lc-assump-generation.simps)
qed

lemma eval-prod-list-var-gen-match:
   assumes (branch-assms, branch-poly-list) ∈ set (lc-assump-generation-list qs
init-assumps)
  assumes ⋀p n. (p,n) ∈ set branch-assms ⟹ satisfies-evaluation val p n
  shows eval-mpoly-poly val (prod-list-var-gen branch-poly-list) =
    prod-list-var-gen (map (eval-mpoly-poly val) branch-poly-list)
  using assms
proof (induct qs arbitrary: branch-assms branch-poly-list init-assumps val)
```

case *Nil*
then have (*branch-assms*, *branch-poly-list*) ∈ *set* [(*init-assumps*, [])]
using *lc-assump-generation-list.simps* **by** *auto*
then have *branch-poly-list* = []
by *simp*
then show *?case*
by *simp*
next
case (*Cons a qs*)
let *?rec* = *lc-assump-generation a init-assumps*
have *inset*: (*branch-assms*,*branch-poly-list*) ∈ *set* (
concat (*map* (
λ(*new-assumps*, *r*). (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)) *?rec*))
using *Cons.prems lc-assump-generation-list.simps*
by *auto*
then obtain *new-assumps r* **where** *deconstruct-prop*:
(*new-assumps*, *r*) ∈ *set ?rec*
(*branch-assms*,*branch-poly-list*) ∈ *set* (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)
using *inset*
by (*metis* (*no-types*, *lifting*) *concat-map-in-set nth-mem prod.collapse split-def*)
then obtain *elem list-rec* **where** *list-rec-prop*:
list-rec = *lc-assump-generation-list qs new-assumps*
elem ∈ *set list-rec*
(*branch-assms*,*branch-poly-list*) = (*fst elem*, *r*#(*snd elem*))
by *auto*
then have *branch-assms-inset*: (*branch-assms*, *snd elem*) ∈ *set* (*lc-assump-generation-list qs new-assumps*)
using *deconstruct-prop* **by** *auto*
then have *set new-assumps* ⊆ *set branch-assms*
using *deconstruct-prop list-rec-prop branch-init-assms-subset*
by *presburger*
have *ris-var*: *r* = *0* ∨ (∃ *i*. *lookup-assump-aux* (*Polynomial.lead-coeff r*)*new-assumps* = *Some i* ∧ *i* ≠ *0*)
using *lc-assump-generation-inv*[*of new-assumps r a init-assumps*] *deconstruct-prop*(*1*)

by *auto*
then have *r-prop*: *r* = *0* ⟷ *eval-mpoly-poly val r* = *0*
by (*metis* ‹*set new-assumps* ⊆ *set branch-assms*› *basic-trans-rules*(*31*) *eval-commutes eval-mpoly-poly-comm-ring-hom.hom-zero leading-coeff-0-iff local.Cons*(*3*) *lookup-assum-aux-mem satisfies-evaluation-nonzero*)
have *eval-mpoly-poly val* (*prod-list-var-gen* (*snd elem*)) =
prod-list-var-gen (*map* (*eval-mpoly-poly val*) (*snd elem*))
using *Cons.hyps list-rec-prop*
using *branch-assms-inset local.Cons*(*3*) **by** *blast*
then show *?case* **using** *r-prop list-rec-prop*(*3*)
by (*simp add*: *eval-mpoly-poly-comm-ring-hom.hom-mult*)

qed

lemma *map-branch-poly-list*:
  assumes (*branch-assms*, *branch-poly-list*) ∈ *set* (*lc-assump-generation-list qs init-assumps*)
  assumes ⋀*p n*. (*p*,*n*) ∈ *set branch-assms* ⟹ *satisfies-evaluation val p n*
  shows (*map* (*eval-mpoly-poly val*) *qs*) = (*map* (*eval-mpoly-poly val*) *branch-poly-list*)
  using *assms*
proof (*induct qs arbitrary*: *branch-assms branch-poly-list init-assumps*)
  case *Nil*
  then have (*branch-assms*, *branch-poly-list*) ∈ *set* [(*init-assumps*, [])]
    using *lc-assump-generation-list.simps* **by** *auto*
  then have *branch-poly-list* = []
    by *simp*
  then show *?case*
    using *Nil.prems*(*1*)
    by *meson*
next
  case (*Cons a qs*)
  let *?rec* = *lc-assump-generation a init-assumps*
  have *inset*: (*branch-assms*,*branch-poly-list*) ∈ *set* (
    concat (*map* (
      λ(*new-assumps*, *r*). (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
       map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)) *?rec*))
    using *Cons.prems lc-assump-generation-list.simps*
    by *auto*
  then obtain *new-assumps r* **where** *deconstruct-prop*:
    (*new-assumps*, *r*) ∈ *set ?rec*
    (*branch-assms*,*branch-poly-list*) ∈ *set* (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
      map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)
    using *inset*
   by (*metis* (*no-types*, *lifting*) *concat-map-in-set nth-mem prod.collapse split-def*)
  then obtain *elem list-rec* **where** *list-rec-prop*:
    list-rec = *lc-assump-generation-list qs new-assumps*
    elem ∈ *set list-rec*
    (*branch-assms*,*branch-poly-list*) = (*fst elem*, *r*#(*snd elem*))
    by *auto*
 then have *branch-assms-inset*: (*branch-assms*, *snd elem*) ∈ *set* (*lc-assump-generation-list qs new-assumps*)
    using *deconstruct-prop* **by** *auto*
  then have *map-prop*: *map* (*eval-mpoly-poly val*) (*qs*) =
    map (*eval-mpoly-poly val*) (*snd elem*) **using** *Cons.hyps Cons.prems*
    by *blast*
  have *set new-assumps* ⊆ *set branch-assms*
   using *deconstruct-prop list-rec-prop branch-assms-inset branch-init-assms-subset*

    by *presburger*
  then have *eval-mpoly-poly val r* = *eval-mpoly-poly val a*

```
    using branch-poly-eval
    by (meson basic-trans-rules(31) deconstruct-prop(1) local.Cons(3))
  then show ?case
    using map-prop list-rec-prop(3)
    by simp
qed

lemma check-constant-degree-match:
  assumes (a, q) ∈ set (lc-assump-generation init-q init-assumps)
  assumes ⋀p n. (p,n) ∈ set a ⟹ satisfies-evaluation val p n
  shows Polynomial.degree q = Polynomial.degree (eval-mpoly-poly val init-q)
  using assms
proof (induct init-q init-assumps arbitrary: q a rule: lc-assump-generation-induct
)
  case (Base init-q init-assumps)
  then show ?case
    using lc-assump-generation.simps
    by simp
next
  case (Rec init-q init-assumps)
  then show ?case using lc-assump-generation.simps
   by (metis branch-poly-eval degree-0 degree-valuation eval-mpoly-poly-comm-ring-hom.hom-zero
lc-assump-generation-inv lookup-assum-aux-mem)
next
  case (Lookup0 init-q init-assumps)
  then show ?case  using lc-assump-generation.simps
   by (metis branch-poly-eval degree-0 degree-valuation eval-mpoly-poly-comm-ring-hom.hom-zero
lc-assump-generation-inv lookup-assum-aux-mem)
next
  case (LookupN0 init-q init-assumps r)
  then show ?case
    using lc-assump-generation.simps
   by (metis branch-poly-eval degree-0 degree-valuation eval-mpoly-poly-comm-ring-hom.hom-zero
lc-assump-generation-inv lookup-assum-aux-mem)
qed

lemma check-constant-degree-match-list:
   assumes (branch-assms, branch-poly-list) ∈ set (lc-assump-generation-list qs
init-assumps)
  assumes ⋀p n. (p,n) ∈ set branch-assms ⟹ satisfies-evaluation val p n
  shows (check-all-const-deg-gen branch-poly-list) = (check-all-const-deg-gen (map
(eval-mpoly-poly val) qs))
  using assms
proof (induct qs arbitrary: branch-assms branch-poly-list init-assumps)
  case Nil
  then have (branch-assms, branch-poly-list) ∈ set [(init-assumps, [])]
    using lc-assump-generation-list.simps
    by auto
  then have branch-poly-list = []
```

```
    by simp
  then show ?case
    by simp
next
  case (Cons a qs)
  let ?rec = lc-assump-generation a init-assumps
  have inset: (branch-assms,branch-poly-list) ∈ set (
    concat (map (
     λ(new-assumps, r). (let list-rec = lc-assump-generation-list qs new-assumps in
      map (λelem. (fst elem, r#(snd elem))) list-rec) ) ?rec ))
    using Cons.prems lc-assump-generation-list.simps
    by auto
  then obtain new-assumps r where deconstruct-prop:
    (new-assumps, r) ∈ set ?rec
    (branch-assms,branch-poly-list) ∈ set (let list-rec = lc-assump-generation-list qs
new-assumps in
      map (λelem. (fst elem, r#(snd elem))) list-rec)
    using inset
   by (metis (no-types, lifting) concat-map-in-set nth-mem prod.collapse split-def)
  then obtain elem list-rec where list-rec-prop:
    list-rec = lc-assump-generation-list qs new-assumps
    elem ∈ set list-rec
    (branch-assms,branch-poly-list) = (fst elem, r#(snd elem))
    by auto
 then have branch-assms-inset: (branch-assms, snd elem) ∈ set (lc-assump-generation-list
qs new-assumps)
    using deconstruct-prop by auto
 then have ind-prop: (check-all-const-deg-gen (snd elem)) = (check-all-const-deg-gen
(map (eval-mpoly-poly val) qs)) using Cons.hyps Cons.prems
    by blast
  have set new-assumps ⊆ set branch-assms
   using deconstruct-prop list-rec-prop branch-assms-inset branch-init-assms-subset

    by presburger
  then have Polynomial.degree r = Polynomial.degree (eval-mpoly-poly val a)
    using check-constant-degree-match
    by (meson basic-trans-rules(31) deconstruct-prop(1) local.Cons(3))
  then show ?case
    using ind-prop list-rec-prop(3)
    by simp
qed

lemma check-all-const-deg-match:
  shows check-all-const-deg qs = check-all-const-deg-gen qs
proof (induct qs)
  case Nil
  then show ?case by auto
next
  case (Cons a qs)
```

```
  then show ?case by auto
qed

lemma prod-list-var-match:
  shows prod-list-var-gen qs = prod-list-var qs
proof (induct qs)
  case Nil
  then show ?case by auto
next
  case (Cons a qs)
  then show ?case by auto
qed

lemma sign-lead-coeff-on-branch:
  assumes (a, q) ∈ set (lc-assump-generation init-q init-assumps)
  assumes q ≠ 0
  assumes ⋀p n. (p,n) ∈ set a ⟹ satisfies-evaluation val p n
  shows ((Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff q) a))) =
   Sturm-Tarski.sign (Polynomial.lead-coeff (eval-mpoly-poly val q))
  using assms
proof (induct init-q init-assumps arbitrary: q a rule: lc-assump-generation-induct
)
  case (Base init-q init-assumps)
  then show ?case using lc-assump-generation.simps
    by simp
next
  case (Rec init-q init-assumps)
  let ?zero = lc-assump-generation (one-less-degree init-q) ((Polynomial.lead-coeff
init-q, (0::rat)) # init-assumps)
  let ?one  = ((Polynomial.lead-coeff init-q, (1::rat)) # init-assumps, init-q)
   let ?minus-one  = ((Polynomial.lead-coeff init-q, (−1::rat)) # init-assumps,
init-q)
  have inset: (a, q) ∈ set (?one#?minus-one#?zero)
    using Rec.hyps lc-assump-generation.simps Rec(4)
    by auto
  { assume ∗ : (a, q) = ?one
    then have h1: Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff q) a)
= (1::rat)
      by auto
    have h2: satisfies-evaluation val (Polynomial.lead-coeff q) (1)
      using Rec.hyps
      by (metis ∗ Pair-inject Rec.prems(3) list.set-intros(1))
     then have h3: Sturm-Tarski.sign (Polynomial.lead-coeff (eval-mpoly-poly val
q)) = (1::int)
      unfolding satisfies-evaluation-def eval-mpoly-def
      using eval-mpoly-def[of val Polynomial.lead-coeff q] h2 lead-coeff-valuation[of
val q 1]
      by auto
    have Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff q) a) =
```

```
    ((Sturm-Tarski.sign (Polynomial.lead-coeff (eval-mpoly-poly val q))))
    using h1 h3
    by auto
  } moreover {
   assume * : (a, q) = ?minus-one
   then have h1: Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff q) a)
= (−1::rat)
    by auto
   have h2: satisfies-evaluation val (Polynomial.lead-coeff q) (−1)
    using Rec.hyps
    by (metis * Pair-inject Rec.prems(3) list.set-intros(1))
  then have h3: rat-of-int (Sturm-Tarski.sign (Polynomial.lead-coeff (eval-mpoly-poly
val q))) = (−1::rat)
    unfolding satisfies-evaluation-def eval-mpoly-def
    using h2
   by (metis Sturm-Tarski.sign-def[of 1] class-field.neg-1-not-0 degree-valuation[of
val q − 1]
       eval-mpoly-def[of val Polynomial.lead-coeff q]
      eval-mpoly-map-poly-comm-ring-hom.base.coeff-map-poly-hom[of val q Poly-
nomial.degree q]
       eval-mpoly-poly-def[of val q] int-SN.default-gt-zero of-int-eq-1-iff[of 1]
      of-int-hom.hom-uminus[of 1] of-int-hom.injectivity[of − Sturm-Tarski.sign
1]
       of-int-pos[of 1] sign-uminus[of 1])
   have Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff q) a) =
    ((Sturm-Tarski.sign (Polynomial.lead-coeff (eval-mpoly-poly val q))))
    using h1 h3
    by (metis of-int-eq-iff of-rat-of-int-eq)
  }
  moreover {
   assume * : (a, q) ∈ set ?zero
   then have (a, q)
   ∈ set (lc-assump-generation (Multiv-Poly-Props.one-less-degree init-q)
         ((Polynomial.lead-coeff init-q, 0) # init-assumps))
    by auto
   then have set ((Polynomial.lead-coeff init-q, 0) # init-assumps) ⊆ set a
    using lc-assump-generation-subset by presburger
  then have ⋀p n. (p, n) ∈ set ((Polynomial.lead-coeff init-q, 0) # init-assumps)
⟹ satisfies-evaluation val p n
    using Rec.prems by auto
   then have Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff q) a) =
    Sturm-Tarski.sign (Polynomial.lead-coeff (eval-mpoly-poly val q))
    using Rec.hyps Rec.prems
     by (smt (verit, ccfv-SIG) * Sturm-Tarski.sign-cases more-arith-simps(10)
neg-one-neq-one sign-uminus)

  }
  ultimately show ?case using lc-assump-generation.simps
    inset
```

```
    by (smt (verit, del-insts) set-ConsD)
next
  case (Lookup0 init-q init-assumps)
  then show ?case using lc-assump-generation.simps
    by auto

next
  case (LookupN0 init-q init-assumps r)
  then have match: (a, q) = (init-assumps, init-q)
    using lc-assump-generation.simps by auto
  then obtain i where i-prop: i ≠ 0
    lookup-assump-aux (Polynomial.lead-coeff init-q) init-assumps = Some i
    (Polynomial.lead-coeff init-q, i) ∈ set init-assumps
    using LookupN0.prems LookupN0.hyps
    by (meson lookup-assum-aux-mem)
  then have (Polynomial.lead-coeff init-q, i) ∈ set a
    using match by auto
  then have sat-eval: satisfies-evaluation val (Polynomial.lead-coeff init-q) i
    using LookupN0(6) by blast
  have Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff q) a)
   = Sturm-Tarski.sign i
    using i-prop match lookup-assump-aux-subset-consistent-sign
    by simp
  then show ?case
   by (smt (verit, del-insts) LookupN0(6) LookupN0.prems(1) sat-eval branch-poly-eval
i-prop(1) lead-coeff-valuation of-int-hom.injectivity satisfies-evaluation-def)
qed

lemma sign-lead-coeff-on-branch-init:
  assumes (a, q) ∈ set (lc-assump-generation init-q init-assumps)
  assumes q ≠ 0
  assumes ⋀p n. (p,n) ∈ set a ⟹ satisfies-evaluation val p n
  shows Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff q) a) =
   Sturm-Tarski.sign (Polynomial.lead-coeff (eval-mpoly-poly val init-q))
  using sign-lead-coeff-on-branch branch-poly-eval
  by (metis assms(1) assms(2) assms(3))

lemma pos-limit-point-on-branch:
  assumes (a, q) ∈ set (lc-assump-generation init-q init-assumps)
  assumes ⋀p n. (p,n) ∈ set a ⟹ satisfies-evaluation val p n
  shows rat-of-int (Sturm-Tarski.sign (sgn-pos-inf (eval-mpoly-poly val q))) =
     (if q = 0 then 0 else Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff
q) a))
  using assms
proof −
  have rat-of-int (Sturm-Tarski.sign (sgn-pos-inf (eval-mpoly-poly val q))) =
    Sturm-Tarski.sign (Polynomial.lead-coeff (eval-mpoly-poly val q))
    unfolding sgn-pos-inf-def
    by auto
```

then show *?thesis* **using** *sign-lead-coeff-on-branch assms*
by (*smt* (*verit*, *del-insts*) *eval-mpoly-poly-comm-ring-hom.hom-zero leading-coeff-0-iff sign-simps*(*2*))

qed

lemma *pos-limit-point-on-branch-init*:
assumes (*a*, *q*) ∈ *set* (*lc-assump-generation init-q init-assumps*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set a* ⟹ *satisfies-evaluation val p n*
shows *rat-of-int* (*Sturm-Tarski.sign* (*sgn-pos-inf* (*eval-mpoly-poly val init-q*))) =

(*if q* = *0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff q*) *a*))
using *assms pos-limit-point-on-branch sign-lead-coeff-on-branch-init*
using *branch-poly-eval* **by** *force*

lemma *pos-limit-point-on-branch-list*:
assumes (*branch-assms*, *branch-poly-list*) ∈ *set* (*lc-assump-generation-list qs init-assumps*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set branch-assms* ⟹ *satisfies-evaluation val p n*
assumes (*pos-limit-branch*, *neg-limit-branch*) = *limit-points-on-branch* (*branch-assms*, *branch-poly-list*)
shows *map rat-of-int* (*sgn-pos-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*)) = *pos-limit-branch*
using *assms*
proof (*induct qs arbitrary*: *pos-limit-branch neg-limit-branch branch-assms branch-poly-list init-assumps*)
case *Nil*
then have (*branch-assms*, *branch-poly-list*) ∈ *set* [(*init-assumps*, [])]
using *lc-assump-generation-list.simps*
by *auto*
then have *branch-poly-list* = []
by *simp*
then show *?case* **using** *Nil.prems*
unfolding *eval-mpoly-poly-def sgn-pos-inf-rat-list-def*
by *auto*
next
case (*Cons a qs*)
let *?rec* = *lc-assump-generation a init-assumps*
have *inset*: (*branch-assms*,*branch-poly-list*) ∈ *set* (
concat (*map* (
λ(*new-assumps*, *r*). (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)) *?rec*))
using *Cons.prems lc-assump-generation-list.simps*
by *auto*
then obtain *new-assumps r* **where** *deconstruct-prop*:
(*new-assumps*, *r*) ∈ *set ?rec*
(*branch-assms*,*branch-poly-list*) ∈ *set* (*let list-rec* = *lc-assump-generation-list qs new-assumps in*

map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)
using *inset*
by (*metis* (*no-types*, *lifting*) *concat-map-in-set nth-mem prod.collapse split-def*)
then obtain *elem list-rec* **where** *list-rec-prop*:
list-rec = *lc-assump-generation-list qs new-assumps*
elem ∈ *set list-rec*
(*branch-assms*,*branch-poly-list*) = (*fst elem*, *r*#(*snd elem*))
by *auto*
then have *snd-elem-inset*: (*branch-assms*, *snd elem*) ∈ *set* (*lc-assump-generation-list qs new-assumps*)
using *deconstruct-prop* **by** *auto*
obtain *pos-limit-sublist neg-limit-sublist* **where** *sublist-prop*:
(*pos-limit-sublist*, *neg-limit-sublist*) = *limit-points-on-branch* (*branch-assms*, *snd elem*)
by *auto*
then have *ind-prop*: *pos-limit-sublist* = *map rat-of-int* (*sgn-pos-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*))
using *snd-elem-inset Cons.hyps Cons.prems*
by *blast*
have *sublist-connection*: *pos-limit-branch* = (*if r* = *0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*))#*pos-limit-sublist*
using *Cons.prems*(*3*) *sublist-prop list-rec-prop*(*3*)
by *simp*
have *list-prop*: *map* (λ*x*. *rat-of-int* (*Sturm-Tarski.sign* (*sgn-pos-inf x*)))
(*map* (*eval-mpoly-poly val*) (*a*#*qs*)) =
(*rat-of-int* (*Sturm-Tarski.sign* (*sgn-pos-inf* (*eval-mpoly-poly val a*)))) # *map* (λ*x*. *rat-of-int* (*Sturm-Tarski.sign* (*sgn-pos-inf x*)))
(*map* (*eval-mpoly-poly val*) *qs*)
by *simp*
have *tail-prop*: *pos-limit-branch* =
(*if r* = *0 then 0*
else Sturm-Tarski.sign
(*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*)) #
map (λ*x*. *rat-of-int* (*Sturm-Tarski.sign* (*sgn-pos-inf x*)))
(*map* (*eval-mpoly-poly val*) *qs*)
using *sublist-connection ind-prop* **unfolding** *sgn-pos-inf-rat-list-def*
by *auto*
have *subs*: *set new-assumps* ⊆ *set branch-assms*
using *deconstruct-prop list-rec-prop snd-elem-inset branch-init-assms-subset*
by *presburger*
then have *r-sign*: *rat-of-int* (*Sturm-Tarski.sign* (*sgn-pos-inf* (*eval-mpoly-poly val a*))) =
(*if r* = *0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *new-assumps*))
using *pos-limit-point-on-branch-init deconstruct-prop*(*1*) *local.Cons*(*3*) *subsetD*
by (*smt* (*verit*, *ccfv-threshold*))
have *r-inv*: *r* = (*0*::*rmpoly*) ∨ (∃ *i*. (*lookup-assump-aux* (*Polynomial.lead-coeff r*) *new-assumps* = *Some i* ∧ *i* ≠ *0*))
using *lc-assump-generation-inv*

by (*meson deconstruct-prop*(*1*))
have *r-match*: (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *new-assumps*))
= (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*))
proof −
{assume ∗: *r = 0*
then have (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *new-assumps*))
= (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*))
by *auto*
} moreover {assume ∗: *r ≠ 0*
then obtain *i1* **where** *i1-prop*: *lookup-assump-aux* (*Polynomial.lead-coeff r*) *new-assumps = Some i1 ∧ i1 ≠ 0*
using *r-inv* **by** *auto*
then obtain *i2* **where** *i2-prop*: *lookup-assump-aux* (*Polynomial.lead-coeff r*) *branch-assms = Some i2 ∧ i2 ≠ 0*
using *lookup-assump-aux-subset-consistency subs*
using *Cons.prems*(*2*) **by** *blast*
then have *Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *new-assumps*) =
Sturm-Tarski.sign (*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*)
using *lookup-assump-aux-subset-consistent-sign subs*
i1-prop i2-prop Cons.prems(*2*)
proof −
obtain *mm* :: *real list* ⇒ (*real mpoly* × *rat*) *list* ⇒ *real mpoly* **and** *rr* :: *real list* ⇒ (*real mpoly* × *rat*) *list* ⇒ *rat* **where**
∀ *x4 x5*. (∃ *v6 v7*. (*v6*, *v7*) ∈ *set x5* ∧ ¬ *satisfies-evaluation x4 v6 v7*) = ((*mm x4 x5*, *rr x4 x5*) ∈ *set x5* ∧ ¬ *satisfies-evaluation x4* (*mm x4 x5*) (*rr x4 x5*))
by *moura*
then have ∀ *ps rs psa p r ra*. ((*mm rs ps*, *rr rs ps*) ∈ *set ps* ∧ ¬ *satisfies-evaluation rs* (*mm rs ps*) (*rr rs ps*) ∨ ¬ *set psa* ⊆ *set ps* ∨ *lookup-assump-aux* (*Polynomial.lead-coeff p*) *psa ≠ Some r* ∨ *lookup-assump-aux* (*Polynomial.lead-coeff p*) *ps ≠ Some ra*) ∨ (*Sturm-Tarski.sign r*) = *Sturm-Tarski.sign ra*
by (*meson lookup-assump-aux-subset-consistent-sign*)
then have (*Sturm-Tarski.sign i1*) = *Sturm-Tarski.sign i2*
using *i1-prop i2-prop local.Cons*(*3*) *subs* **by** *blast*
then show *?thesis*
by (*simp add*: *i1-prop i2-prop*)
qed

then have (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *new-assumps*))
= (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*))
by *auto*
}
ultimately show *?thesis*

```
    by auto
  qed
  then have rat-of-int (Sturm-Tarski.sign (sgn-pos-inf (eval-mpoly-poly val a))) =

     (if r = 0 then 0 else Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff
r) branch-assms))
    using r-sign r-match
    by fastforce
  then have pos-limit-branch = (rat-of-int (Sturm-Tarski.sign (sgn-pos-inf (eval-mpoly-poly
val a)))) #
    (map (λx. rat-of-int (Sturm-Tarski.sign (sgn-pos-inf x)))
     (map (eval-mpoly-poly val) qs))
    using tail-prop
   by (smt (verit, ccfv-threshold) list.inj-map-strong list.map(2) of-rat-hom.eq-iff)

  then show ?case using  list-prop
    using sgn-pos-inf-rat-list-def
    by (auto)
qed

lemma neg-limit-point-on-branch-init:
  assumes (a, q) ∈ set (lc-assump-generation init-q init-assumps)
  assumes ⋀p n. (p,n) ∈ set a ⟹ satisfies-evaluation val p n
  shows rat-of-int (Sturm-Tarski.sign (sgn-neg-inf (eval-mpoly-poly val init-q))) =

     (if q = 0 then 0 else (Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff
q) a))*(-1)^(Polynomial.degree q))
proof -
  have at-inf: rat-of-int
     (Sturm-Tarski.sign  (sgn-class.sgn (Polynomial.lead-coeff (eval-mpoly-poly val
init-q)))) =
    (if q = 0 then 0
     else Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff q) a))
    using assms  pos-limit-point-on-branch-init
    unfolding sgn-pos-inf-def
    by auto
  have Polynomial.degree q = Polynomial.degree (eval-mpoly-poly val init-q)
    using check-constant-degree-match assms by auto
  then show ?thesis using at-inf
    unfolding sgn-neg-inf-def
   using Sturm-Tarski-casting degree-0 even-zero more-arith-simps(6) more-arith-simps(8)
ring-1-class.minus-one-power-iff by auto

qed

lemma neg-limit-point-on-branch-list:
   assumes (branch-assms, branch-poly-list) ∈ set (lc-assump-generation-list qs
init-assumps)
  assumes ⋀p n. (p,n) ∈ set branch-assms ⟹ satisfies-evaluation val p n
```

assumes (*pos-limit-branch*, *neg-limit-branch*) = *limit-points-on-branch* (*branch-assms*, *branch-poly-list*)
shows *map rat-of-int* (*sgn-neg-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*)) = *neg-limit-branch*
using *assms*
proof (*induct qs arbitrary*: *pos-limit-branch neg-limit-branch branch-assms branch-poly-list init-assumps*)
case *Nil*
then have (*branch-assms*, *branch-poly-list*) ∈ *set* [(*init-assumps*, [])]
using *lc-assump-generation-list.simps*
by *auto*
then have *branch-poly-list* = []
by *simp*
then show *?case* **using** *Nil.prems*
unfolding *eval-mpoly-poly-def sgn-neg-inf-rat-list-def*
by *auto*
next
case (*Cons a qs*)
let *?rec* = *lc-assump-generation a init-assumps*
have *inset*: (*branch-assms*,*branch-poly-list*) ∈ *set* (
concat (*map* (
λ(*new-assumps*, *r*). (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)) *?rec*))
using *Cons.prems lc-assump-generation-list.simps*
by *auto*
then obtain *new-assumps r* **where** *deconstruct-prop*:
(*new-assumps*, *r*) ∈ *set ?rec*
(*branch-assms*,*branch-poly-list*) ∈ *set* (*let list-rec* = *lc-assump-generation-list qs new-assumps in*
map (λ*elem*. (*fst elem*, *r*#(*snd elem*))) *list-rec*)
using *inset*
by (*metis* (*no-types*, *lifting*) *concat-map-in-set nth-mem prod.collapse split-def*)
then obtain *elem list-rec* **where** *list-rec-prop*:
list-rec = *lc-assump-generation-list qs new-assumps*
elem ∈ *set list-rec*
(*branch-assms*,*branch-poly-list*) = (*fst elem*, *r*#(*snd elem*))
by *auto*
then have *snd-elem-inset*: (*branch-assms*, *snd elem*) ∈ *set* (*lc-assump-generation-list qs new-assumps*)
using *deconstruct-prop* **by** *auto*
obtain *pos-limit-sublist neg-limit-sublist* **where** *sublist-prop*:
(*pos-limit-sublist*, *neg-limit-sublist*) = *limit-points-on-branch* (*branch-assms*, *snd elem*)
by *auto*
then have *ind-prop-var*: *neg-limit-sublist* = *map rat-of-int* (*sgn-neg-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*))
using *snd-elem-inset Cons.hyps Cons.prems* **by** *blast*
then have *ind-prop*: *neg-limit-sublist* = *sgn-neg-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*)

by *auto*
have *sublist-connection*: *pos-limit-branch* = (*if r* = *0 then 0 else Sturm-Tarski.sign*
(*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*))#*pos-limit-sublist*
using *Cons.prems*(*3*) *sublist-prop list-rec-prop*(*3*)
by *simp*
then have *sublist-connection-var*: *pos-limit-branch* = (*if r* = *0 then 0 else*
(*rat-of-int* ∘ *Sturm-Tarski.sign*) (*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*))#*pos-limit-sublist*
using *Cons.prems*(*3*) *sublist-prop list-rec-prop*(*3*)
by *simp*
have *list-prop*: *map* (λ*x*. *rat-of-int* (*Sturm-Tarski.sign* (*sgn-neg-inf x*)))
(*map* (*eval-mpoly-poly val*) (*a*#*qs*)) =
(*rat-of-int* (*Sturm-Tarski.sign* (*sgn-neg-inf* (*eval-mpoly-poly val a*)))) # *map* (λ*x*.
rat-of-int (*Sturm-Tarski.sign* (*sgn-neg-inf x*)))
(*map* (*eval-mpoly-poly val*) *qs*)
by *simp*
have *ind-prop-var2*: *neg-limit-sublist* =
(*map* (λ*x*. (*rat-of-int* ∘ *Sturm-Tarski.sign*) (*sgn-neg-inf x*))
(*map* (*eval-mpoly-poly val*) *qs*))
using *ind-prop-var* **unfolding** *sgn-neg-inf-rat-list-def*
by *auto*
have *neg-limit-branch* =
(*if r* = *0 then* (*0*::*rat*)
else ((*rat-of-int* ∘ *Sturm-Tarski.sign*)
(*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*)∗(−*1*)^(*Polynomial.degree*
r))) #
map (λ*x*. ((*rat-of-int* ∘ *Sturm-Tarski.sign*) (*sgn-neg-inf x*)))
(*map* (*eval-mpoly-poly val*) *qs*)
using *sublist-connection-var ind-prop-var2 local.Cons*(*4*) **unfolding** *sgn-neg-inf-rat-list-def*

unfolding *limit-points-on-branch.simps*
by (*metis* (*no-types*, *lifting*) *limit-points-on-branch.simps list.simps*(*9*) *list-rec-prop*(*3*)
prod.simps(*1*) *sublist-prop*)
then have *tail-prop-helper*: *neg-limit-branch* =
(*if r* = *0 then 0*
else rat-of-int (*Sturm-Tarski.sign*
(*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*)∗(−*1*)^(*Polynomial.degree*
r))) #
map (λ*x*. *rat-of-int* (*Sturm-Tarski.sign* (*sgn-neg-inf x*)))
(*map* (*eval-mpoly-poly val*) *qs*)
by *auto*
then have *tail-prop*: *neg-limit-branch* =
(*if r* = *0 then 0*
else Sturm-Tarski.sign
(*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*)∗(−*1*)^(*Polynomial.degree*
r)) #
map (λ*x*. *rat-of-int* (*Sturm-Tarski.sign* (*sgn-neg-inf x*)))
(*map* (*eval-mpoly-poly val*) *qs*)
by (*smt* (*verit*, *ccfv-threshold*) *list.map*(*2*) *of-int-hom.hom-zero of-rat-of-int-eq*)
have *subs*: *set new-assumps* ⊆ *set branch-assms*

using *deconstruct-prop list-rec-prop snd-elem-inset branch-init-assms-subset*
by *presburger*
then have *r-sign*: *rat-of-int* (*Sturm-Tarski.sign* (*sgn-neg-inf* (*eval-mpoly-poly val a*))) =
(*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *new-assumps*)∗(−1)^(*Polynomial.degree r*))
using *neg-limit-point-on-branch-init deconstruct-prop*(*1*) *local.Cons*(*3*) *subsetD*
by (*smt* (*verit*, *ccfv-threshold*))
have *r-inv*: *r* = (*0*::*rmpoly*) ∨ (∃ *i*. (*lookup-assump-aux* (*Polynomial.lead-coeff r*) *new-assumps* = *Some i* ∧ *i* ≠ *0*))
using *lc-assump-generation-inv*
by (*meson deconstruct-prop*(*1*))
have *r-match-pre*: (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *new-assumps*))
= (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*))
proof −
{assume ∗: *r* = *0*
then have (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *new-assumps*))
= (*if r = 0 then 0 else Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*))
by *auto*
} moreover {assume ∗: *r* ≠ *0*
then obtain *i1* **where** *i1-prop*: *lookup-assump-aux* (*Polynomial.lead-coeff r*) *new-assumps* = *Some i1* ∧ *i1* ≠ *0*
using *r-inv* **by** *auto*
then obtain *i2* **where** *i2-prop*: *lookup-assump-aux* (*Polynomial.lead-coeff r*) *branch-assms* = *Some i2* ∧ *i2* ≠ *0*
using *lookup-assump-aux-subset-consistency subs*
using *Cons.prems*(*2*) **by** *blast*
then have *Sturm-Tarski.sign* (*lookup-assump* (*Polynomial.lead-coeff r*) *new-assumps*) =
Sturm-Tarski.sign (*lookup-assump* (*Polynomial.lead-coeff r*) *branch-assms*)
using *lookup-assump-aux-subset-consistent-sign subs*
i1-prop i2-prop Cons.prems(*2*)
proof −
obtain *mm* :: *real list* ⇒ (*real mpoly* × *rat*) *list* ⇒ *real mpoly* **and** *rr* :: *real list* ⇒ (*real mpoly* × *rat*) *list* ⇒ *rat* **where**
∀ *x4 x5*. (∃ *v6 v7*. (*v6*, *v7*) ∈ *set x5* ∧ ¬ *satisfies-evaluation x4 v6 v7*) = ((*mm x4 x5*, *rr x4 x5*) ∈ *set x5* ∧ ¬ *satisfies-evaluation x4* (*mm x4 x5*) (*rr x4 x5*))
by *moura*
then have ∀ *ps rs psa p r ra*. ((*mm rs ps*, *rr rs ps*) ∈ *set ps* ∧ ¬ *satisfies-evaluation rs* (*mm rs ps*) (*rr rs ps*) ∨ ¬ *set psa* ⊆ *set ps* ∨ *lookup-assump-aux* (*Polynomial.lead-coeff p*) *psa* ≠ *Some r* ∨ *lookup-assump-aux* (*Polynomial.lead-coeff p*) *ps* ≠ *Some ra*) ∨ (*Sturm-Tarski.sign r*) = *Sturm-Tarski.sign ra*
by (*meson lookup-assump-aux-subset-consistent-sign*)
then have (*Sturm-Tarski.sign i1*) = *Sturm-Tarski.sign i2*
using *i1-prop i2-prop local.Cons*(*3*) *subs* **by** *blast*

```
      then show ?thesis
        by (simp add: i1-prop i2-prop)
    qed

    then have (if r = 0 then 0 else Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff
r) new-assumps))
      = (if r = 0 then 0 else Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff
r) branch-assms))
        by auto
    }
    ultimately show ?thesis
      by auto
  qed
   then have r-match: (if r = 0 then 0 else Sturm-Tarski.sign (lookup-assump
(Polynomial.lead-coeff r) new-assumps)*(-1)^(Polynomial.degree r))
=  (if r = 0 then 0 else Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff
r) branch-assms)*(-1)^(Polynomial.degree r))
    by metis
  then have rat-of-int (Sturm-Tarski.sign (sgn-neg-inf (eval-mpoly-poly val a)))
=
     (if r = 0 then 0 else Sturm-Tarski.sign (lookup-assump (Polynomial.lead-coeff
r) branch-assms)*(-1)^(Polynomial.degree r))
    using r-sign r-match
    by fastforce
 then have neg-limit-branch = (rat-of-int (Sturm-Tarski.sign (sgn-neg-inf (eval-mpoly-poly
val a)))) #
    (map (λx. rat-of-int (Sturm-Tarski.sign (sgn-neg-inf x)))
     (map (eval-mpoly-poly val) qs))
    using tail-prop tail-prop-helper
    by (simp add: of-rat-hom.injectivity)
  then show ?case using  list-prop
    using sgn-neg-inf-rat-list-def
    by auto
qed

lemma complex-rat-casting-lemma:
  fixes a:: int list
  fixes b:: rat list
  shows map complex-of-int a = map of-rat b ⟹ map rat-of-int a = b
 by (metis (no-types, lifting) list.inj-map-strong list.map-comp of-rat-hom.injectivity
of-rat-of-int)

lemma complex-rat-casting-lemma-sets:
  fixes a:: rat list list
  fixes b1:: int list
  fixes b2:: int list
  fixes c:: rat list list
  assumes set (map (map of-rat) a) ∪ {map complex-of-int b1, map complex-of-int
b2}
```

```
    = set (map (map of-rat) c)
  shows set a ∪ {map rat-of-int b1, map rat-of-int b2} = set c
proof −
  have map complex-of-int b1 ∈ set (map (map of-rat) c)
    using assms by auto
  then have h1: map rat-of-int b1 ∈ set c
    using complex-rat-casting-lemma by auto
  have map complex-of-int b2 ∈ set (map (map of-rat) c)
    using assms by auto
  then have h2: map rat-of-int b2 ∈ set c
    using complex-rat-casting-lemma by auto
  have set-lem: ⋀ a b c . a ∪ b = c ⟹ a ⊆ c
    by blast
  have set (map (map of-rat) a) ⊆ set (map (map of-rat) c)
    using assms set-lem[of set (map (map of-rat) a) {map complex-of-int b1, map
complex-of-int b2} set (map (map of-rat) c)]
    by auto
  then have ⋀x. x ∈ set (map (map of-rat) a) ⟹ x ∈ set (map (map of-rat) c)
    by auto
  then have h3: ⋀x. x ∈ set a ⟹ x ∈ set c
    using complex-rat-casting-lemma
    by fastforce
  have h4-a: ⋀x. x ∈ set (map (map of-rat) c) ⟹
       x ≠ map complex-of-int b1 ⟹ x ∉ set (map (map of-rat) a) ⟹ x = map
complex-of-int b2
    using assms
    by blast
  have h4: ⋀x. x ∈ set c ⟹
       x ≠ map rat-of-int b1 ⟹ x ∉ set a ⟹ x = map rat-of-int b2
  proof −
    fix x
    assume a1: x ∈ set c
    assume a2: x ≠ map rat-of-int b1
    assume a3: x ∉ set a
    have ((map of-rat x)::complex list) ∈ set (map (map of-rat) c)
      using a1 by auto
    then have impl: ((map of-rat x)::complex list) ≠ map complex-of-int b1 ⟹
(map of-rat x) ∉ set (map (map of-rat) a) ⟹ (map of-rat x) = map complex-of-int
b2
      using h4-a[of ((map of-rat x)::complex list)]
      using a3 imageE inj-map-eq-map list.set-map of-rat-hom.inj-f by fastforce
    have impl-h1: ((map of-rat x)::complex list) ≠ map complex-of-int b1
      using a2 complex-rat-casting-lemma
      by metis
    have impl-h2: (map of-rat x) ∉ set (map (map of-rat) a)
      using a3 complex-rat-casting-lemma by (auto)
    then have (map of-rat x) = map complex-of-int b2
      using impl impl-h1 impl-h2 by auto
    then show x = map rat-of-int b2
```

using *complex-rat-casting-lemma* **by** *metis*
qed
show *?thesis* **using** *h1 h2 h3 h4* **by** *auto*
qed

lemma *complex-rat-casting-lemma-sets2*:
shows {*map rat-of-int*
(*map* (λ*x*. *Sturm-Tarski.sign* (*sgn-neg-inf x*))
(*map* (*eval-mpoly-poly val*) *qs*)),
map rat-of-int
(*map* (λ*x*. *Sturm-Tarski.sign* (*sgn-pos-inf x*))
(*map* (*eval-mpoly-poly val*) *qs*))} = {*map* (λ*x*. (*rat-of-int* ∘ *Sturm-Tarski.sign*) (*sgn-neg-inf x*))
(*map* (*eval-mpoly-poly val*) *qs*),
map (λ*x*. (*rat-of-int* ∘ *Sturm-Tarski.sign*) (*sgn-pos-inf x*))
(*map* (*eval-mpoly-poly val*) *qs*)}
proof −
have *h1*: *map rat-of-int*
(*map* (λ*x*. *Sturm-Tarski.sign* (*sgn-neg-inf x*))
(*map* (*eval-mpoly-poly val*) *qs*)) = *map* (λ*x*. (*rat-of-int* ∘ *Sturm-Tarski.sign*) (*sgn-neg-inf x*))
(*map* (*eval-mpoly-poly val*) *qs*)
by *auto*
have *h2*: *map rat-of-int*
(*map* (λ*x*. *Sturm-Tarski.sign* (*sgn-pos-inf x*))
(*map* (*eval-mpoly-poly val*) *qs*)) = *map* (λ*x*. (*rat-of-int* ∘ *Sturm-Tarski.sign*) (*sgn-pos-inf x*))
(*map* (*eval-mpoly-poly val*) *qs*)
by *auto*
show *?thesis* **using** *h1 h2*
by *auto*
qed

lemma *sign-determination-inner-gives-noncomp-signs-at-roots*:
assumes (*assumps*, *signs*) ∈ *set* (*sign-determination-inner qs init-assumps*)
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
shows *set signs* = (*consistent-sign-vectors-R* (*map* (*eval-mpoly-poly val*) *qs*) *UNIV*)
proof −
have *elem-in-set*: (*assumps*, *signs*) ∈ *set* (*let branches* = *lc-assump-generation-list qs init-assumps in*
concat (*map* (λ*branch*.
let poly-p-branch = *poly-p-in-branch branch*;
(*pos-limit-branch*, *neg-limit-branch*) = *limit-points-on-branch branch*;
calculate-data-branch = *extract-signs* (*calculate-data-assumps-M poly-p-branch* (*snd branch*) (*fst branch*))
in map (λ(*a*, *signs*). (*a*, *pos-limit-branch*#*neg-limit-branch*#*signs*)) *calculate-data-branch*
) *branches*))

using *assms*
by *auto*
obtain *branch* **where** *branch-prop*: *branch* ∈ *set* (*lc-assump-generation-list qs init-assumps*)
(*assumps*, *signs*) ∈ *set* (
let poly-p-branch = *poly-p-in-branch branch*;
(*pos-limit-branch*, *neg-limit-branch*) = *limit-points-on-branch branch*;
calculate-data-branch = *extract-signs* (*calculate-data-assumps-M poly-p-branch* (*snd branch*) (*fst branch*))
in map (λ(*a*, *signs*). (*a*, *pos-limit-branch*#*neg-limit-branch*#*signs*)) *calculate-data-branch*)
using *elem-in-set*
by *auto*
then obtain *branch-assms branch-poly-list* **where** *branch-is*:
branch = (*branch-assms*, *branch-poly-list*)
using *poly-p-in-branch.cases* **by** *blast*
then obtain *calculate-data-branch poly-p-branch pos-limit-branch neg-limit-branch*
where *branch-prop-expanded*:
poly-p-branch = *poly-p-in-branch branch*
(*pos-limit-branch*, *neg-limit-branch*) = *limit-points-on-branch branch*
calculate-data-branch = *extract-signs* (*calculate-data-assumps-M poly-p-branch branch-poly-list branch-assms*)
branch ∈ *set* (*lc-assump-generation-list qs init-assumps*)
(*assumps*, *signs*) ∈ *set* (
map (λ(*a*, *signs*). (*a*, *pos-limit-branch*#*neg-limit-branch*#*signs*)) *calculate-data-branch*)
using *branch-prop*
by (*metis* (*no-types*, *lifting*) *case-prod-beta fst-conv prod.exhaust-sel snd-conv*)
obtain *calc-a calc-signs* **where** *calc-prop*:
(*calc-a*, *calc-signs*) ∈ *set calculate-data-branch*
(*assumps*, *signs*) = (*calc-a*, *pos-limit-branch*#*neg-limit-branch*#*calc-signs*)
using *branch-prop-expanded*(*5*)
by *auto*
then have *branch-assms-subset*: *set branch-assms* ⊆ *set assumps*
using *branch-prop-expanded*(*3*) *extract-signs-M-subset*
by *blast*
have *set init-assumps* ⊆ *set branch-assms*
using *branch-is branch-prop*(*1*) *branch-init-assms-subset*
by *blast*
have *assumps-calc-a*: *assumps* = *calc-a*
using *calc-prop* **by** *auto*
let *?poly-p-branch* = *poly-p-in-branch* (*branch-assms*, *branch-poly-list*)
have *nonz-poly-p*: *eval-mpoly-poly val ?poly-p-branch* ≠ *0*
using *poly-p-nonzero-on-branch*
using ‹*set branch-assms* ⊆ *set assumps*› *assms*(*2*) *branch-is branch-prop*(*1*) **by** *blast*
have *map-branch-poly-list*: (*map* (*eval-mpoly-poly val*) *qs*) = (*map* (*eval-mpoly-poly val*) *branch-poly-list*)
using *map-branch-poly-list*
using *assms*(*2*) *branch-assms-subset branch-is branch-prop*(*1*) **by** *blast*

have (*calc-a*, *calc-signs*)
∈ *set* (*calculate-data-to-signs* (*calculate-data-assumps-M poly-p-branch branch-poly-list branch-assms*))
using *calc-prop branch-prop-expanded calc-data-to-signs-and-extract-signs*
by *metis*
then have (*assumps*, *calc-signs*)
∈ *set* (*calculate-data-to-signs* (*calculate-data-assumps-M poly-p-branch branch-poly-list branch-assms*))
using *assumps-calc-a* **by** *auto*
then have *set calc-signs* = *set*(*characterize-consistent-signs-at-roots* (*eval-mpoly-poly val ?poly-p-branch*) (*map* (*eval-mpoly-poly val*) *branch-poly-list*))
using *nonz-poly-p calculate-data-assumps-gives-noncomp-signs-at-roots*[*of assumps signs poly-p-branch branch-poly-list branch-assms val*]
using *assms*(*2*) *branch-is branch-prop-expanded*(*1*) *calculate-data-assumps-gives-noncomp-signs-at-roots* **by** *blast*
then have *calc-signs-is*: *set calc-signs* = *set*(*characterize-consistent-signs-at-roots* (*eval-mpoly-poly val ?poly-p-branch*) (*map* (*eval-mpoly-poly val*) *qs*))
using *map-branch-poly-list* **by** *auto*
have *poly-p-is*: *poly-p-in-branch* (*branch-assms*, *branch-poly-list*) = (*if* (*check-all-const-deg-gen branch-poly-list* = *True*) *then* [:*0*, *1*:] *else*
(*pderiv* (*prod-list-var-gen branch-poly-list*)) ∗ (*prod-list-var-gen branch-poly-list*))
by *auto*
have *const-match*: (*check-all-const-deg-gen branch-poly-list*) = (*check-all-const-deg-gen* (*map* (*eval-mpoly-poly val*) *qs*))
using *check-constant-degree-match-list*
using *assms*(*2*) *branch-assms-subset branch-is branch-prop*(*1*) **by** *blast*
have *eval-mpoly-poly val* (*prod-list-var-gen branch-poly-list*) =
prod-list-var-gen (*map* (*eval-mpoly-poly val*) *branch-poly-list*)
using *eval-prod-list-var-gen-match*
using *assms*(*2*) *branch-assms-subset branch-is branch-prop*(*1*) **by** *blast*
then have *same-prod*: *eval-mpoly-poly val* ((*pderiv* (*prod-list-var-gen branch-poly-list*)) ∗ (*prod-list-var-gen branch-poly-list*))
= *pderiv* (*prod-list-var-gen* (*map* (*eval-mpoly-poly val*) *branch-poly-list*)) ∗ (*prod-list-var-gen* (*map* (*eval-mpoly-poly val*) *branch-poly-list*))
by (*metis eval-mpoly-poly-comm-ring-hom.hom-mult pderiv-commutes*)
{assume ∗: *check-all-const-deg-gen branch-poly-list* = *True*
then have *?poly-p-branch* = [: *0*, *1* :]
using *poly-p-is* **by** *presburger*
then have (*eval-mpoly-poly val ?poly-p-branch*) = [:*0*, *1*:]
unfolding *eval-mpoly-poly-def*
by *auto*
then have (*eval-mpoly-poly val ?poly-p-branch*) = (*poly-f-nocrb* (*map* (*eval-mpoly-poly val*) *qs*))
unfolding *poly-f-nocrb-def* **using** *const-match check-all-const-deg-match* ∗
by *presburger*
}
moreover {assume ∗: *check-all-const-deg-gen branch-poly-list* = *False*
then have (*eval-mpoly-poly val ?poly-p-branch*) = *pderiv* (*prod-list-var-gen* (*map* (*eval-mpoly-poly val*) *branch-poly-list*)) ∗ (*prod-list-var-gen* (*map* (*eval-mpoly-poly*

val) *branch-poly-list*))
using *poly-p-is same-prod* **by** *auto*
then have *h1*: (*eval-mpoly-poly val ?poly-p-branch*) = *pderiv* (*prod-list-var-gen* (*map* (*eval-mpoly-poly val*) *qs*)) ∗ (*prod-list-var-gen* (*map* (*eval-mpoly-poly val*) *qs*))
using *map-branch-poly-list*
by *presburger*
have (*check-all-const-deg* (*map* (*eval-mpoly-poly val*) *qs*) = *False*)
using ∗ *const-match check-all-const-deg-match* **by** *auto*
then have (*eval-mpoly-poly val ?poly-p-branch*) = (*poly-f-nocrb* (*map* (*eval-mpoly-poly val*) *qs*))
using *h1 prod-list-var-match*
unfolding *poly-f-nocrb-def*
by *metis*
}
ultimately have *poly-branch-no-crb-connect*: (*eval-mpoly-poly val ?poly-p-branch*) = (*poly-f-nocrb* (*map* (*eval-mpoly-poly val*) *qs*))
by *auto*
let *?eval-qs* = (*map* (*eval-mpoly-poly val*) *qs*)
have *set calc-signs* =
set (*characterize-consistent-signs-at-roots* (*poly-f-nocrb ?eval-qs*) *?eval-qs*)
using *poly-branch-no-crb-connect calc-signs-is*
by *presburger*

then have *calc-signs-relation*: (*set calc-signs*) ∪ {*sgn-neg-inf-rat-list ?eval-qs*, *sgn-pos-inf-rat-list ?eval-qs*} =
set (*characterize-consistent-signs-at-roots* (*poly-f ?eval-qs*) *?eval-qs*)
using *poly-f-ncrb-connection*[*of ?eval-qs*]
by *auto*

then have *set calc-signs* ∪
{*map rat-of-int*
(*sgn-neg-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*)),
map rat-of-int
(*sgn-pos-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*))} =
set (*characterize-consistent-signs-at-roots*
(*poly-f* (*map* (*eval-mpoly-poly val*) *qs*))
(*map* (*eval-mpoly-poly val*) *qs*))
unfolding *sgn-neg-inf-rat-list2-def sgn-pos-inf-rat-list2-def*
using *complex-rat-casting-lemma-sets*[*of calc-signs* (*sgn-neg-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*)) (*sgn-pos-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*))
(*characterize-consistent-signs-at-roots* (*poly-f* (*map* (*eval-mpoly-poly val*) *qs*)) (*map* (*eval-mpoly-poly val*) *qs*))]
by (*auto*)
then have *calc-signs-relation-var*: (*set calc-signs*) ∪ ({*sgn-neg-inf-rat-list2 ?eval-qs*, *sgn-pos-inf-rat-list2 ?eval-qs*}::*rat list set*) =
set (*characterize-consistent-signs-at-roots* (*poly-f ?eval-qs*) *?eval-qs*)
unfolding *sgn-neg-inf-rat-list2-def sgn-pos-inf-rat-list2-def sgn-neg-inf-rat-list-def sgn-pos-inf-rat-list-def*
using *complex-rat-casting-lemma-sets2*

by *auto*
have *pos-inf*: *sgn-pos-inf-rat-list ?eval-qs = pos-limit-branch*
using *branch-prop-expanded*(*2*) *pos-limit-point-on-branch-list*
using *assms*(*2*) *branch-assms-subset branch-is branch-prop*(*1*)
by (*smt* (*verit*, *ccfv-threshold*) *basic-trans-rules*(*31*) *list.map-comp of-rat-of-int*)
then have *pos-inf-var*: *sgn-pos-inf-rat-list2 ?eval-qs = pos-limit-branch*
unfolding *sgn-pos-inf-rat-list2-def*
using *complex-rat-casting-lemma*[*of* (*sgn-pos-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*)) *pos-limit-branch*]
unfolding *sgn-pos-inf-rat-list-def* **by** *auto*
have *neg-inf*: *sgn-neg-inf-rat-list ?eval-qs = neg-limit-branch*
using *branch-prop-expanded*(*2*) *neg-limit-point-on-branch-init*
using *assms*(*2*) *branch-assms-subset branch-is branch-prop*(*1*)
by (*smt* (*verit*, *ccfv-SIG*) *basic-trans-rules*(*31*) *list.map-comp neg-limit-point-on-branch-list of-rat-of-int*)
then have *neg-inf-var*: *sgn-neg-inf-rat-list2 ?eval-qs = neg-limit-branch*
unfolding *sgn-neg-inf-rat-list2-def*
using *complex-rat-casting-lemma*[*of* (*sgn-neg-inf-rat-list* (*map* (*eval-mpoly-poly val*) *qs*)) *neg-limit-branch*]
unfolding *sgn-neg-inf-rat-list-def*
by *auto*
have *set signs = set* (*characterize-consistent-signs-at-roots* (*poly-f ?eval-qs*) *?eval-qs*)
using *calc-signs-relation-var pos-inf-var neg-inf-var calc-prop*(*2*)
unfolding *sgn-neg-inf-rat-list2-def sgn-pos-inf-rat-list2-def*
by *auto*
then show *set signs* = (*consistent-sign-vectors-R* (*map* (*eval-mpoly-poly val*) *qs*) *UNIV*)
using *find-consistent-signs-at-roots-R poly-f-ncrb-connection calc-signs-is main-step-R*
by (*metis find-consistent-signs-R-def poly-f-nonzero*)
qed

17.10 Completeness

lemma *lc-assump-generation-valuation*:
assumes $\bigwedge p\ n.\ (p,n) \in$ *set init-assumps* $\Longrightarrow$ *satisfies-evaluation val p n*
shows $\exists$ *branch* $\in$ *set* (*lc-assump-generation q init-assumps*).
set (*fst branch*) $\subseteq$ *set* (*init-assumps*) $\cup$ *set*
(*map* ($\lambda x.$ (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs q*))
using *assms*
proof (*induct q init-assumps rule*: *lc-assump-generation-induct*)
case (*Base q assumps*)
then show *?case*
using *lc-assump-generation.simps* **by** *auto*
next
case (*Rec q assumps*)
let *?zero = lc-assump-generation* (*one-less-degree q*) ((*Polynomial.lead-coeff q*, (*0*::*rat*)) # *assumps*)
let *?one* = ((*Polynomial.lead-coeff q*, (*1*::*rat*)) # *assumps*, *q*)

let *?minus-one* = ((*Polynomial.lead-coeff q*, (−*1*::*rat*)) # *assumps*, *q*)
have *set-is*: *set* (*lc-assump-generation q assumps*) = *set* (*?one*#*?minus-one*#*?zero*)
using *Rec.hyps Rec*(*4*) *lc-assump-generation.simps* **by** *auto*
let *?lc* = (*Polynomial.lead-coeff q*)
have *eo*: *satisfies-evaluation val ?lc* (*0*::*rat*) ∨ *satisfies-evaluation val ?lc* (*1*::*rat*)
∨ *satisfies-evaluation val ?lc* (−*1*::*rat*)
unfolding *satisfies-evaluation-def eval-mpoly-def Sturm-Tarski.sign-def* **by** *auto*
{assume ∗: *satisfies-evaluation val ?lc* (*1*::*rat*)
then have *1* = *mpoly-sign val* (*Polynomial.lead-coeff q*)
unfolding *satisfies-evaluation-def eval-mpoly-def mpoly-sign-def Sturm-Tarski.sign-def*
by *simp*
then have (*Polynomial.lead-coeff q*, *1*) ∈ *set* (*map* (λ*x*. (*x*, *mpoly-sign val x*))
(*Polynomial.coeffs q*))
by (*simp add*: *Rec*(*1*) *coeff-in-coeffs*)
then have *set* (*fst ?one*) ⊆ *set assumps* ∪ *set* (*map* (λ*x*. (*x*, *mpoly-sign val x*))
(*Polynomial.coeffs q*))
by *auto*
then have ∃ *branch*∈*set* (*lc-assump-generation q assumps*).
set (*fst branch*) ⊆ *set assumps* ∪ *set* (*map* (λ*x*. (*x*, *mpoly-sign val x*))
(*Polynomial.coeffs q*))
using *set-is* **by** *auto*
} moreover
{assume ∗: *satisfies-evaluation val ?lc* (−*1*::*rat*)
then have −*1* = *mpoly-sign val* (*Polynomial.lead-coeff q*)
unfolding *satisfies-evaluation-def eval-mpoly-def mpoly-sign-def Sturm-Tarski.sign-def*
by (*smt* (*z3*) *of-int-1 of-int-minus rel-simps*(*66*) *zero-neq-neg-one*)
then have (*Polynomial.lead-coeff q*, −*1*) ∈ *set* (*map* (λ*x*. (*x*, *mpoly-sign val*
x)) (*Polynomial.coeffs q*))
by (*simp add*: *Rec*(*1*) *coeff-in-coeffs*)
then have *set* (*fst ?minus-one*) ⊆ *set assumps* ∪ *set* (*map* (λ*x*. (*x*, *mpoly-sign*
val x)) (*Polynomial.coeffs q*))
by *auto*
then have ∃ *branch*∈*set* (*lc-assump-generation q assumps*).
set (*fst branch*) ⊆ *set assumps* ∪ *set* (*map* (λ*x*. (*x*, *mpoly-sign val x*))
(*Polynomial.coeffs q*))
using *set-is* **by** *auto*
} moreover {assume ∗: *satisfies-evaluation val ?lc* (*0*::*rat*)
then have ∃ *branch*∈*set* (*lc-assump-generation* (*Multiv-Poly-Props.one-less-degree*
q) ((*Polynomial.lead-coeff q*, *0*) # *assumps*)).
set (*fst branch*)
⊆ *set* ((*Polynomial.lead-coeff q*, *0*) # *assumps*) ∪
set (*map* (λ*x*. (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs* (*Multiv-Poly-Props.one-less-degree*
q)))
using *lc-assump-generation.simps*
using *Rec*(*3*) *Rec*(*4*) **by** *fastforce*
then obtain *branch* **where** *branch-prop*: *branch*∈*set* (*lc-assump-generation*
(*Multiv-Poly-Props.one-less-degree q*) ((*Polynomial.lead-coeff q*, *0*) # *assumps*))
set (*fst branch*)
⊆ *set* ((*Polynomial.lead-coeff q*, *0*) # *assumps*) ∪

set (*map* (λ*x*. (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs* (*Multiv-Poly-Props.one-less-degree q*)))
by *auto*
then have *branch-prop-2*: *branch*∈*set ?zero*
by *auto*
have *0* = *mpoly-sign val* (*Polynomial.lead-coeff q*) **using** ∗
unfolding *satisfies-evaluation-def eval-mpoly-def mpoly-sign-def Sturm-Tarski.sign-def*
by *simp*
then have *lc-sign*: (*Polynomial.lead-coeff q*, *0*) ∈ *set* (*map* (λ*x*. (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs q*))
by (*simp add*: *Rec*(*1*) *coeff-in-coeffs*)
{assume ∗∗: *Multiv-Poly-Props.one-less-degree q* ≠ *0*
then have *set* (*Polynomial.coeffs* (*Multiv-Poly-Props.one-less-degree q*)) ⊆ *set* (*Polynomial.coeffs q*)
using *coeff-one-less-degree-subset* **unfolding** *Polynomial.coeffs-def*
by *blast*
then have *set* (*fst branch*) ⊆ *set assumps* ∪
set (*map* (λ*x*. (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs q*))
using *branch-prop*
by (*smt* (*verit*, *del-insts*) *UnCI UnE lc-sign imageE image-eqI list.set-map set-ConsD subset-code*(*1*))
then have ∃ *branch*∈*set* (*lc-assump-generation q assumps*).
set (*fst branch*)
⊆ *set assumps* ∪
set (*map* (λ*x*. (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs q*))
using *branch-prop-2*
using *set-is* **by** *force*
}
moreover {assume ∗∗: *Multiv-Poly-Props.one-less-degree q* = *0*
then have ∃ *branch*∈*set* (*lc-assump-generation q assumps*).
set (*fst branch*) ⊆ *set assumps* ∪
set (*map* (λ*x*. (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs q*))
using *Rec.hyps*(*2*) *UnCI lc-sign insert-subset lc-assump-generation.elims list.set*(*2*) *option.case*(*1*) *prod.sel*(*1*) *subsetI*
by (*metis* (*no-types*, *lifting*))
}
ultimately have ∃ *branch*∈*set* (*lc-assump-generation q assumps*).
set (*fst branch*) ⊆ *set assumps* ∪ *set* (*map* (λ*x*. (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs q*))
by *auto*
}
ultimately show *?case* **using** *eo* **by** *auto*
next
case (*Lookup0 q assumps*)
then obtain *branch* **where** *branch-prop*:*branch*∈*set* (*lc-assump-generation* (*Multiv-Poly-Props.one-less-degree q*) *assumps*)
set (*fst branch*)
⊆ *set assumps* ∪ *set* (*map* (λ*x*. (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs* (*Multiv-Poly-Props.one-less-degree q*)))

```
    by auto
  have same-gen: lc-assump-generation (one-less-degree q) assumps = lc-assump-generation
q assumps
    using Lookup0.hyps lc-assump-generation.simps by auto
  then have branch-prop-2 :branch∈set (lc-assump-generation q assumps)
    using branch-prop(1) by auto
  {assume ∗: Multiv-Poly-Props.one-less-degree q ≠ 0
    then have set (Polynomial.coeffs (Multiv-Poly-Props.one-less-degree q)) ⊆ set
(Polynomial.coeffs q)
      using coeff-one-less-degree-subset unfolding Polynomial.coeffs-def
      by blast
    then have set (fst branch)
      ⊆ set assumps ∪
        set (map (λx. (x, mpoly-sign val x)) (Polynomial.coeffs q))
      using branch-prop-2 branch-prop(2) by auto
    then have ∃ branch∈set (lc-assump-generation q assumps).
      set (fst branch)
      ⊆ set assumps ∪
        set (map (λx. (x, mpoly-sign val x)) (Polynomial.coeffs q))
      using branch-prop-2
      by auto
  }
  moreover {assume ∗: Multiv-Poly-Props.one-less-degree q = 0
    then have ∃ branch∈set (lc-assump-generation q assumps).
      set (fst branch)
      ⊆ set assumps ∪
        set (map (λx. (x, mpoly-sign val x)) (Polynomial.coeffs q))
     by (simp add: Lookup0(2) lc-assump-generation.simps)
  }
  ultimately show ?case
    by force
next
  case (LookupN0 q assumps r)
  then show ?case using lc-assump-generation.simps
    by simp
qed

lemma lc-assump-generation-valuation-satisfies-eval:
  fixes q:: rmpoly
  assumes (p,n) ∈ set (map (λx. (x, mpoly-sign val x)) ell)
  shows satisfies-evaluation val p n
proof −
  obtain c where c-prop: c ∈ set ell
    (p, n) = (c, mpoly-sign val c)
    using assms by auto
  have satisfies-evaluation val c (mpoly-sign val c)
    unfolding satisfies-evaluation-def mpoly-sign-def eval-mpoly-def
      Sturm-Tarski.sign-def by auto
  then show ?thesis
```

using *c-prop* **by** *auto*
qed

lemma *lc-assump-generation-list-valuation*:
assumes $\bigwedge p\ n.\ (p,n) \in$ *set init-assumps* $\Longrightarrow$ *satisfies-evaluation val p n*
shows $\exists$ *branch* $\in$ *set* (*lc-assump-generation-list qs init-assumps*).
set (*fst branch*) $\subseteq$ *set* (*init-assumps*) $\cup$ *set*
(*map* ($\lambda x.$ (*x*, *mpoly-sign val x*)) (*coeffs-list qs*))
using *assms*
proof (*induct qs arbitrary*: *init-assumps*)
case *Nil*
then show *?case*
using *lc-assump-generation-list.simps*
by *simp*
next
case (*Cons a qs*)
then obtain *branch-a* **where** *branch-a-prop*: *branch-a* $\in$ *set* (*lc-assump-generation a init-assumps*)
set (*fst branch-a*) $\subseteq$ *set* (*init-assumps*) $\cup$ *set*
(*map* ($\lambda x.$ (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs a*))
using *lc-assump-generation-valuation*
by *blast*
then obtain *branch-a-assms branch-a-poly* **where** *branch-a-is*: *branch-a* = (*branch-a-assms*, *branch-a-poly*)
set (*branch-a-assms*) $\subseteq$ *set* (*init-assumps*) $\cup$ *set*
(*map* ($\lambda x.$ (*x*, *mpoly-sign val x*)) (*Polynomial.coeffs a*))
by (*meson prod.exhaust-sel*)
have *inset*: *set* (*map* (λ*elem.* (*fst elem*, *branch-a-poly*#(*snd elem*))) (*lc-assump-generation-list qs branch-a-assms*))
$\subseteq$ *set* (*lc-assump-generation-list* (*a*#*qs*) *init-assumps*)
using *lc-assump-generation-list.simps branch-a-is*(*1*) *branch-a-prop*(*1*)
by *auto*
have $\bigwedge p\ n.\ (p,n) \in$ *set branch-a-assms* $\Longrightarrow$ *satisfies-evaluation val p n*
using *lc-assump-generation-valuation-satisfies-eval branch-a-is*(*1*) *fst-conv local.Cons*(*2*) *Set.basic-monos*(*7*) *UnE*
proof −
fix *p* :: *real mpoly* **and** *n* :: *rat*
assume (*p*, *n*) $\in$ *set branch-a-assms*
then show *satisfies-evaluation val p n*
by (*meson UnE lc-assump-generation-valuation-satisfies-eval Set.basic-monos*(*7*) *branch-a-is*(*2*) *local.Cons*(*2*))
qed
then obtain *branch* **where** *branch-props*:
branch∈*set* (*lc-assump-generation-list qs branch-a-assms*)
set (*fst branch*)
$\subseteq$ *set branch-a-assms* $\cup$
set (*map* ($\lambda x.$ (*x*, *mpoly-sign val x*)) (*coeffs-list qs*))
using *Cons.hyps*[*of branch-a-assms*] **by** *auto*

```
  then have branch-inset:
    (fst branch, branch-a-poly#(snd branch))
    ∈ set (lc-assump-generation-list (a#qs) init-assumps)
    using inset
    by auto
  then have subset-h: set (fst branch) ⊆ set (init-assumps) ∪ (set
      (map (λx. (x, mpoly-sign val x)) (Polynomial.coeffs a))
    ∪ set (map (λx. (x, mpoly-sign val x)) (coeffs-list qs)))
    using branch-props(2) branch-a-is(2) by auto
  have coeffs-list (a # qs) = (Polynomial.coeffs a) @ (coeffs-list qs)
    unfolding coeffs-list-def by auto
  then have same-set:
    set (map (λx. (x, mpoly-sign val x)) (coeffs-list (a#qs))) = (set
      (map (λx. (x, mpoly-sign val x)) (Polynomial.coeffs a))
    ∪ set (map (λx. (x, mpoly-sign val x)) (coeffs-list qs)))
    by auto
  then have set (fst branch) ⊆ set (init-assumps) ∪ set
      (map (λx. (x, mpoly-sign val x)) (coeffs-list (a#qs)))
    using subset-h by auto
  then show ?case
    using branch-inset
    by (metis (no-types, lifting) prod.sel(1))
qed

lemma base-case-info-M-assumps-complete:
  assumes ⋀p n. (p,n) ∈ set init-assumps ⟹ satisfies-evaluation val p n
  shows ∃ (assumps, mat-eq) ∈ set (base-case-info-M-assumps init-assumps).
   (∀ (p,n) ∈ set assumps. satisfies-evaluation val p n)
  using assms unfolding base-case-info-M-assumps-def by auto

lemma matches-len-complete-spmods-ex:
  assumes ⋀p' n'. (p',n') ∈ set acc ⟹ satisfies-evaluation val p' n'
  shows ∃(assumps, sturm-seq) ∈ set (spmods-multiv p q acc).
    (∀ (p,n) ∈ set assumps. satisfies-evaluation val p n)
  using assms
proof (induct p q acc rule: spmods-multiv-induct)
  case (Base p q acc)
  then show ?case
    by (auto simp add: spmods-multiv.simps)
next
  case (Rec p q acc)
 let ?left = spmods-multiv (one-less-degree p) q ((Polynomial.lead-coeff p, (0::rat))
# acc)
  let ?res-one = spmods-multiv-aux p q ((Polynomial.lead-coeff p, (1::rat)) # acc)
 let ?res-minus-one = spmods-multiv-aux p q ((Polynomial.lead-coeff p, (−1::rat))
# acc)
  have spmods-is: spmods-multiv p q acc = ?left @ (?res-one @ ?res-minus-one)
    using spmods-multiv.simps Rec(1−2) by auto
  have satisfies-evaluation val (Polynomial.lead-coeff p) 0 ∨
```

satisfies-evaluation val (Polynomial.lead-coeff p) 1 ∨
satisfies-evaluation val (Polynomial.lead-coeff p) (−1)
unfolding *satisfies-evaluation-def*
apply *auto*
using *Sturm-Tarski.sign-cases*
by (*metis of-int-1 of-int-minus*)
then have *q*:
(∀ *p′ n′*. (*p′*,*n′*) ∈ *set* ((*Polynomial.lead-coeff p*, *0*) # *acc*) ⟶ *satisfies-evaluation val p′ n′*) ∨
(∀ *p′ n′*. (*p′*,*n′*) ∈ *set* ((*Polynomial.lead-coeff p*, *1*) # *acc*) ⟶ *satisfies-evaluation val p′ n′*) ∨
(∀ *p′ n′*. (*p′*,*n′*) ∈ *set* ((*Polynomial.lead-coeff p*, *−1*) # *acc*) ⟶ *satisfies-evaluation val p′ n′*)
using *Rec*
by *simp*
moreover {
assume ∗:(∀ *p′ n′*. (*p′*,*n′*) ∈ *set* ((*Polynomial.lead-coeff p*, *0*) # *acc*) ⟶ *satisfies-evaluation val p′ n′*)
then have ∃ *a*∈*set* (*spmods-multiv* (*Multiv-Poly-Props.one-less-degree p*) *q*
((*Polynomial.lead-coeff p*, *0*) # *acc*)).
case a of
(*a*, *ss*) ⇒
∀ *a*∈*set a*. *case a of* (*a*, *b*) ⇒ *satisfies-evaluation val a b*
using *Rec* **by** *auto*
then have *?case* **using** *spmods-is* **by** *auto*
}
moreover {
assume ∗:(∀ *p′ n′*. (*p′*,*n′*) ∈ *set* ((*Polynomial.lead-coeff p*, *1*) # *acc*) ⟶ *satisfies-evaluation val p′ n′*)
then obtain *assumps sturm-seq* **where**
(*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (*1*::*rat*)) # *acc*))
⋀ *p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
using *matches-len-complete*[*of* ((*Polynomial.lead-coeff p*, (*1*::*rat*)) # *acc*) *val p q*]
by *blast*
then have *?case* **using** *spmods-is* **by** *auto*
}
moreover {
assume ∗:(∀ *p′ n′*. (*p′*,*n′*) ∈ *set* ((*Polynomial.lead-coeff p*, *−1*) # *acc*) ⟶ *satisfies-evaluation val p′ n′*)
then obtain *assumps sturm-seq* **where**
(*assumps*, *sturm-seq*) ∈ *set* (*spmods-multiv-aux p q* ((*Polynomial.lead-coeff p*, (*−1*::*rat*)) # *acc*))
⋀ *p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
using *matches-len-complete*[*of* ((*Polynomial.lead-coeff p*, (*−1*::*rat*)) # *acc*) *val p q*]
by *blast*
then have *?case* **using** *spmods-is* **by** *auto*

```
  }
  ultimately show ?case
    by fastforce
next
  case (Lookup0 p q acc)
  then show ?case  by (auto simp add: spmods-multiv.simps)
next
  case (LookupN0 p q acc r)
  then have spmods-is: spmods-multiv p q acc = spmods-multiv-aux p q acc
    using spmods-multiv.simps by auto
  obtain assumps sturm-seq where
    (assumps, sturm-seq) ∈ set (spmods-multiv-aux p q acc)
    ⋀ p n. (p,n) ∈ set assumps ⟹ satisfies-evaluation val p n
    using LookupN0(4) matches-len-complete[of acc val p q]
    by blast
  then show ?case
    using spmods-is by auto
qed

lemma matches-len-complete-spmods:
  assumes ⋀p n. (p,n) ∈ set acc ⟹ satisfies-evaluation val p n
  obtains assumps sturm-seq where
    (assumps, sturm-seq) ∈ set (spmods-multiv p q acc)
    (f,n) ∈ set assumps ⟹ satisfies-evaluation val f n
  using assms matches-len-complete-spmods-ex
  by (smt (verit, ccfv-threshold) case-prodD case-prodE)

lemma tarski-queries-complete-aux:
  assumes ⋀p n. (p,n) ∈ set init-assumps ⟹ satisfies-evaluation val p n
  shows ∃ (assumps, tq) ∈ set (construct-NofI-R-spmods p init-assumps I1 I2).
   (∀ (p,n) ∈ set assumps. satisfies-evaluation val p n)
  unfolding construct-NofI-R-spmods-def
 using assms matches-len-complete-spmods-ex[of init-assumps val monoid-add-class.sum-list
(map power2 (p # I1))]
  by meson

lemma tarski-queries-complete:
  assumes ⋀p n. (p,n) ∈ set init-assumps ⟹ satisfies-evaluation val p n
  shows ∃ (assumps, tq) ∈ set (construct-NofI-M p init-assumps I1 I2).
   (∀ (p,n) ∈ set assumps. satisfies-evaluation val p n)
proof −
  have cnoi-is: construct-NofI-M p init-assumps I1 I2 =
  (let ss-list = construct-NofI-R-spmods p init-assumps I1 I2 in
  map construct-NofI-single-M ss-list)
    by auto
 obtain assumps tq where assumps-tq: (assumps, tq) ∈ set (construct-NofI-R-spmods
p init-assumps I1 I2)
    (∀ (p,n) ∈ set assumps. satisfies-evaluation val p n)
    using tarski-queries-complete-aux assms
```

by (*smt* (*verit*, *ccfv-threshold*) *case-prodE*)
then have *inset*: *construct-NofI-single-M* (*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps I1 I2*)
by (*metis* (*no-types*, *lifting*) ‹*construct-NofI-M p init-assumps I1 I2* = *Let* (*construct-NofI-R-spmods p init-assumps I1 I2*) (*map construct-NofI-single-M*)› *in-set-conv-nth length-map nth-map*)

obtain *r* **where** (*assumps*, *r*) = *construct-NofI-single-M* (*assumps*, *tq*)
using *construct-NofI-single-M.simps* **by** *auto*
then show *?thesis*
using *inset assumps-tq*(*2*)
by (*smt* (*verit*) *case-prodI*)
qed

lemma *solve-for-rhs-rec-M-complete*:
assumes ⋀*p n*. (*p*,*n*) ∈ *set init-assumps* ⟹ *satisfies-evaluation val p n*
shows ∃ (*assumps*, *rhs-vec*) ∈ *set* (*construct-rhs-vector-rec-M p init-assumps ell*).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *assms* **proof** (*induct ell arbitrary*: *init-assumps*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a ell*)
then obtain *qs1 qs2* **where** *qs-prop*: *a* = (*qs1*, *qs2*)
by (*meson prod.exhaust*)
have ∃ (*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps qs1 qs2*).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *tarski-queries-complete assms*
using *local.Cons*(*2*) **by** *presburger*
then obtain *assumps tq* **where** *assumps-tq*: (*assumps*, *tq*) ∈ *set* (*construct-NofI-M p init-assumps qs1 qs2*)
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
by *blast*
then have *ind-h*: ∃ *a*∈*set* (*construct-rhs-vector-rec-M p assumps ell*).
case a of
(*assumps1*, *rhs-vec1*) ⇒
∀ *a*∈*set assumps1*. *case a of* (*a*, *b*) ⇒ *satisfies-evaluation val a b*
using *Cons.hyps*
by (*metis* (*no-types*, *lifting*) *case-prodD*)
{assume ∗: *ell* = []
then have *construct-rhs-vector-rec-M p init-assumps* ((*qs1*, *qs2*)#[])
= *construct-rhs-vector-rec-M p init-assumps* (*a*#*ell*)
using *qs-prop*
by *blast*
have *rhs-is*: *construct-rhs-vector-rec-M p init-assumps* ((*qs1*, *qs2*)#[]) =
(*let TQ-list* = *construct-NofI-M p init-assumps qs1 qs2 in*
map (λ(*new-assumps*, *tq*). (*new-assumps*, [*tq*])) *TQ-list*)
using ∗ *construct-rhs-vector-rec-M.simps*(*2*) **by** *blast*

```
    have (assumps, [tq]) ∈ set (construct-rhs-vector-rec-M p init-assumps ((qs1,
qs2)#[]))
      using assumps-tq rhs-is
      by (smt (verit, best) image-eqI list.set-map old.prod.case)
    then have ?case using assumps-tq(1)
      using ∗ assumps-tq(2) qs-prop by blast
  } moreover {assume ∗: length ell > 0
    then obtain v va where ell = v#va
      by (meson Suc-le-length-iff Suc-less-eq le-simps(2))
    then have construct-rhs-vector-rec-M p init-assumps ((qs1, qs2)#ell) =
    concat (let TQ-list = construct-NofI-M p init-assumps qs1 qs2 in
    (map (λ(new-assumps, tq). (let rec = construct-rhs-vector-rec-M p new-assumps
ell in
      map (λr. (fst r,  tq#snd r)) rec)) TQ-list))
      using ∗ construct-rhs-vector-rec-M.simps(3) by auto
    then have subset-prop: set (let rec = construct-rhs-vector-rec-M p assumps ell
in
    map (λr. (fst r,  tq#snd r)) rec) ⊆ set (construct-rhs-vector-rec-M p init-assumps
((qs1, qs2)#ell))
      using assumps-tq
      by auto
    then obtain assumps1 rhs-vec1 where assumps1-rhs1:
      (assumps1, rhs-vec1) ∈ set (construct-rhs-vector-rec-M p assumps ell)
      (∀ (p,n) ∈ set assumps1. satisfies-evaluation val p n)
      using ind-h
      by blast
    then have (assumps1, tq#rhs-vec1) ∈ set (let rec = construct-rhs-vector-rec-M
p assumps ell in
      map (λr. (fst r,  tq#snd r)) rec)
        by (metis (no-types, lifting) fst-eqD in-set-conv-nth length-map nth-map
snd-conv)
    then have (assumps1, tq#rhs-vec1) ∈ set (construct-rhs-vector-rec-M p init-assumps
((qs1, qs2)#ell))
      using subset-prop by auto
    then have ?case
      using assumps1-rhs1(2) qs-prop
      by auto
  }
  ultimately show ?case by auto
qed


lemma solve-for-rhs-M-complete:
  assumes ⋀p n. (p,n) ∈ set init-assumps ⟹ satisfies-evaluation val p n
  shows ∃ (assumps, rhs-vec) ∈ set (construct-rhs-vector-M p init-assumps qs Is).
    (∀ (p,n) ∈ set assumps. satisfies-evaluation val p n)
proof −
  obtain assumps rhs-rec-vec where assumps-rec:
    (assumps, rhs-rec-vec) ∈ set (construct-rhs-vector-rec-M p init-assumps (pull-out-pairs
```

qs Is))
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *assms solve-for-rhs-rec-M-complete*
by (*smt* (*verit*, *ccfv-threshold*) *case-prodE*)
then have (*assumps*, *rhs-rec-vec*)
∈ *set* (*construct-rhs-vector-rec-M p init-assumps*
(*map* (λ(*I1*, *I2*). (*retrieve-polys qs I1*, *retrieve-polys qs I2*)) *Is*)) ⟹
(⋀*z f A*. (*z* ∈ *f* ‘ *A*) = (∃ *x*∈*A*. *z* = *f x*)) ⟹
∀ *x*∈*set assumps*. *case x of* (*x*, *xa*) ⇒ *satisfies-evaluation val x xa* ⟹
∃ *x*∈*set* (*construct-rhs-vector-rec-M p init-assumps*
(*map* (λ(*I1*, *I2*). (*retrieve-polys qs I1*, *retrieve-polys qs I2*))
Is)).
∀ *x*∈*set* (*fst x*). *case x of* (*x*, *xa*) ⇒ *satisfies-evaluation val x xa*
by *fastforce*
then show *?thesis*
using *image-iff assumps-rec* **unfolding** *construct-rhs-vector-M-def* **by** *auto*
qed

lemma *solve-for-lhs-M-complete*:
assumes ⋀*p n*. (*p*,*n*) ∈ *set init-assumps* ⟹ *satisfies-evaluation val p n*
shows ∃ (*assumps*, *lhs-vec*) ∈ *set* (*solve-for-lhs-M p init-assumps qs subsets matr*).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
proof −
obtain *assumps rhs-vec* **where** *assumps-prop*:
(*assumps*, *rhs-vec*) ∈ *set* (*construct-rhs-vector-M p init-assumps qs subsets*)
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *solve-for-rhs-M-complete assms*
by (*metis* (*mono-tags*, *lifting*) *prod.simps*(*2*) *surj-pair*)
let *?rhs* = (*assumps*, *rhs-vec*)
have (*assumps*, *rhs-vec*)
∈ *set* (*construct-rhs-vector-M p init-assumps qs subsets*) ⟹
(*assumps*, *solve-for-lhs-single-M p qs subsets matr rhs-vec*)
∈ (λ*rhs*. (*fst rhs*, *solve-for-lhs-single-M p qs subsets matr* (*snd rhs*))) ‘
set (*construct-rhs-vector-M p init-assumps qs subsets*)
using *image-iff* **by** *fastforce*
then have (*fst ?rhs*, *solve-for-lhs-single-M p qs subsets matr* (*snd ?rhs*))
∈ *set* (*solve-for-lhs-M p init-assumps qs subsets matr*)
using *assumps-prop*(*1*) **unfolding** *solve-for-lhs-M-def*
by *auto*
then show *?thesis* **using** *assumps-prop*(*2*)
by *auto*
qed

lemma *reduce-system-single-M-complete*:
assumes ⋀*p n*. (*p*,*n*) ∈ *set init-assumps* ⟹ *satisfies-evaluation val p n*
shows ∃ (*assumps*, *mat-eq*) ∈ *set* (*reduce-system-single-M p qs* (*init-assumps*, (*m*,*subs*,*signs*))).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)

proof −
obtain *assumps lhs-vec* **where** *assumps-lhs*:
(*assumps*, *lhs-vec*) ∈ *set* (*solve-for-lhs-M p init-assumps qs subs m*)
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *assms solve-for-lhs-M-complete*
by (*metis* (*mono-tags*, *lifting*) *split-conv surj-pair*)
then have (*assumps*, *lhs-vec*) ∈ *set* (*solve-for-lhs-M p init-assumps qs subs m*)
⟹
∀ *x*∈*set assumps*. *case x of* (*p*, *n*) ⇒ *satisfies-evaluation val p n* ⟹
(⋀*z f A*. (*z* ∈ *f* ' *A*) = (∃ *x*∈*A*. *z* = *f x*)) ⟹
∃ *x*∈*set* (*solve-for-lhs-M p init-assumps qs subs m*).
∀ *x*∈*set* (*fst x*). *case x of* (*x*, *xa*) ⇒ *satisfies-evaluation val x xa*
by (*metis fst-conv*)
then show *?thesis*
using *assumps-lhs image-iff reduce-system-single-M.simps* **by** *auto*
qed

lemma *reduce-system-M-concat-map-helper*:
fixes *a*:: *'a list*
fixes *b*:: *'a list list*
assumes *a* ∈ *set b*
shows *set a* ⊆ *set* (*concat b*)
using *assms* **by** *auto*

lemma *reduce-system-M-complete*:
assumes ⋀*p n*. (*p*,*n*) ∈ *set init-assumps* ⟹ *satisfies-evaluation val p n*
assumes (*init-assumps*, *mat-eq*) ∈ *set input-list*
shows ∃ (*assumps*, *mat-eq*) ∈ *set* (*reduce-system-M p qs input-list*).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
proof −
obtain *m subs signs* **where** *mat-eq*: (*init-assumps*, (*m*,*subs*,*signs*)) ∈ *set input-list*
using *assms*(*2*)
by (*metis prod-cases3*)
have *reduce*: *reduce-system-M p qs input-list* = *concat* (*map* (*reduce-system-single-M p qs*) *input-list*)
using *reduce-system-M.simps* **by** *auto*
have *elem*: (*reduce-system-single-M p qs* (*init-assumps*, (*m*,*subs*,*signs*))) ∈ *set* (*map* (*reduce-system-single-M p qs*) *input-list*)
using *mat-eq*
by (*metis* (*no-types*, *opaque-lifting*) *image-eqI image-set*)
then have *set* (*reduce-system-single-M p qs* (*init-assumps*, (*m*,*subs*,*signs*))) ⊆ *set* (*concat* (*map* (*reduce-system-single-M p qs*) *input-list*))
using *reduce-system-M-concat-map-helper*[*of* (*reduce-system-single-M p qs* (*init-assumps*, (*m*,*subs*,*signs*))) (*map* (*reduce-system-single-M p qs*) *input-list*)]
by *auto*
then have *subset*: *set* (*reduce-system-single-M p qs* (*init-assumps*, (*m*,*subs*,*signs*))) ⊆ *set*
(*reduce-system-M p qs input-list*)

using *mat-eq reduce* **by** *auto*
have ∃ (*assumps*, *mat-eq*)∈ *set* (*reduce-system-single-M p qs* (*init-assumps*, (*m*,*subs*,*signs*))).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *reduce-system-single-M-complete assms*(*1*)
by *presburger*
then show *?thesis* **using** *subset*
using *basic-trans-rules*(*31*) **by** *blast*
qed

lemma *combine-systems-M-complete*:
assumes (*assumps1*, *mat-eq1*) ∈ *set list1*
assumes (∀ (*p*,*n*) ∈ *set assumps1*. *satisfies-evaluation val p n*)
assumes (*assumps2*, *mat-eq2*) ∈ *set list2*
assumes (∀ (*p*,*n*) ∈ *set assumps2*. *satisfies-evaluation val p n*)
shows ∃ (*assumps*, *mat-eq*) ∈ *set* (*snd* (*combine-systems-M p q1 list1 q2 list2*)).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
proof −
have *snd-is*: *snd* (*combine-systems-M p q1 list1 q2 list2*) = *concat* (*map* (λ*l1*. (*map* (λ*l2*. *combine-systems-single-M p q1 l1 q2 l2*) *list2*)) *list1*)
by *auto*
have (*assumps1*, *mat-eq1*) ∈ *set list1* ⟹
(*assumps2*, *mat-eq2*) ∈ *set list2* ⟹
∃ *x*∈*set list1*.
(*assumps1* @ *assumps2*,
snd (*combine-systems-R p* (*q1*, *mat-eq1*) (*q2*, *mat-eq2*)))
∈ *combine-systems-single-M p q1 x q2* ‘ *set list2*
by (*metis combine-systems-single-M.simps rev-image-eqI*)
then have *inset*: *combine-systems-single-M p q1* (*assumps1*, *mat-eq1*) *q2* (*assumps2*, *mat-eq2*)
∈ *set* (*concat* (*map* (λ*l1*. (*map* (λ*l2*. *combine-systems-single-M p q1 l1 q2 l2*) *list2*)) *list1*))
using *snd-is assms*(*1*) *assms*(*3*) **by** *auto*
obtain *mat-eq* **where** *mat-eq*: (*append assumps1 assumps2*, *mat-eq*) = *combine-systems-single-M p q1* (*assumps1*, *mat-eq1*) *q2* (*assumps2*, *mat-eq2*)
using *combine-systems-single-M.simps* **by** *auto*
then have (*append assumps1 assumps2*, *mat-eq*) ∈
set (*concat* (*map* (λ*l1*. (*map* (λ*l2*. *combine-systems-single-M p q1 l1 q2 l2*) *list2*)) *list1*))
using *inset* **by** *auto*
then have *inset2*: (*append assumps1 assumps2*, *mat-eq*) ∈ *set* (*snd* (*combine-systems-M p q1 list1 q2 list2*))
using *snd-is* **by** *auto*
have ⋀*p n*. (*p*,*n*) ∈ *set* (*append assumps1 assumps2*) ⟹ *satisfies-evaluation val p n*
using *assms*(*2*) *assms*(*4*) **by** *auto*
then show *?thesis*
using *inset2*
by *blast*

qed

lemma *get-all-valuations-calculate-data-M*:
assumes $\bigwedge p\ n.\ (p,n) \in$ *set init-assumps* $\Longrightarrow$ *satisfies-evaluation val p n*
shows $\exists$ (*assumps*, *mat-eq*) $\in$ *set* (*calculate-data-assumps-M p qs init-assumps*).
($\forall$ (*p*,*n*) $\in$ *set assumps*. *satisfies-evaluation val p n*)
using *assms*
proof (*induct length qs arbitrary*: *val p init-assumps qs rule*: *less-induct*)
case (*less qs val p init-assumps*)
have *length qs* = *0* $\vee$ *length qs* = *1* $\vee$ *length qs* > *1*
by (*meson less-one nat-neq-iff*)
{assume $*$: *length qs* = *0*
then have *calc-data-is*: *calculate-data-assumps-M p* [] *init-assumps*
= *map* (λ(*assumps*,(*a*,(*b*,*c*))). (*assumps*, (*a*,*b*,*map* (*drop 1*) *c*))) (*reduce-system-M p* [*1*] (*base-case-info-M-assumps init-assumps*))
using *calculate-data-assumps-M.simps*
by *simp*
obtain *assumps-inbtw mat-eq-inbtw* **where** *inbtw-props*: (*assumps-inbtw*, *mat-eq-inbtw*) $\in$ *set* (*base-case-info-M-assumps init-assumps*)
($\forall$ (*p*,*n*) $\in$ *set assumps-inbtw*. *satisfies-evaluation val p n*)
using *base-case-info-M-assumps-complete less*(*2*)
by (*metis* (*no-types*, *lifting*) *case-prodE*)
then have ($\bigwedge p\ n.\ (p,\ n) \in$ *set assumps-inbtw* $\Longrightarrow$ *satisfies-evaluation val p n*)
by *auto*
then have $\exists$ (*assumps*, *mat-eq*) $\in$ *set* (*reduce-system-M p* [*1*] (*base-case-info-M-assumps init-assumps*)).
($\forall$ (*p*,*n*) $\in$ *set assumps*. *satisfies-evaluation val p n*)
using *reduce-system-M-complete*[*of assumps-inbtw val mat-eq-inbtw* (*base-case-info-M-assumps init-assumps*) *p* [*1*]] *inbtw-props*(*1*)
by *fastforce*
then obtain *assumps mat-eq* **where** *assumps-mat*: (*assumps*, *mat-eq*) $\in$ *set* (*reduce-system-M p* [*1*] (*base-case-info-M-assumps init-assumps*))
($\forall$ (*p*,*n*) $\in$ *set assumps*. *satisfies-evaluation val p n*)
by *blast*
then obtain *a b c* **where** *mat-eq* = (*a*, (*b*, *c*))
by (*metis prod.exhaust-sel*)
then have (*assumps*, (*a*, (*b*, *c*))) $\in$ *set* (*reduce-system-M p* [*1*] (*base-case-info-M-assumps init-assumps*))
using *assumps-mat*(*1*) **by** *auto*
then have (*assumps*, (*a*,*b*,*map* (*drop 1*) *c*)) $\in$ *set* (*calculate-data-assumps-M p* [] *init-assumps*)
using *calc-data-is image-iff*
by (*smt* (*z3*) *image-set split-conv*)
then have $\exists$ (*assumps*, *mat-eq*) $\in$ *set* (*calculate-data-assumps-M p qs init-assumps*).
($\forall$ (*p*,*n*) $\in$ *set assumps*. *satisfies-evaluation val p n*)
using *assumps-mat*(*2*) $*$ **by** *blast*
} moreover
{assume $*$: *length qs* = *1*
then have *calc-data-is*: *calculate-data-assumps-M p qs init-assumps* = *re-*

duce-system-M p qs (*base-case-info-M-assumps init-assumps*)
by *auto*
obtain *assumps-inbtw mat-eq-inbtw* **where** *inbtw-props*: (*assumps-inbtw*, *mat-eq-inbtw*) ∈ *set* (*base-case-info-M-assumps init-assumps*)
(∀ (*p*,*n*) ∈ *set assumps-inbtw*. *satisfies-evaluation val p n*)
using *base-case-info-M-assumps-complete less*(*2*)
by (*metis* (*no-types*, *lifting*) *case-prodE*)
then have (⋀*p n*. (*p*, *n*) ∈ *set assumps-inbtw* ⟹ *satisfies-evaluation val p n*)
by *auto*
then have ∃ (*assumps*, *mat-eq*) ∈ *set* (*reduce-system-M p qs* (*base-case-info-M-assumps init-assumps*)).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *reduce-system-M-complete*[*of assumps-inbtw val mat-eq-inbtw* (*base-case-info-M-assumps init-assumps*) *p qs*] *inbtw-props*(*1*)
by *fastforce*
then have ∃ (*assumps*, *mat-eq*) ∈ *set* (*calculate-data-assumps-M p qs init-assumps*).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *calc-data-is* **by** *auto*
} moreover
{assume ∗: *length qs* > *1*
let *?len* = *length qs*
have *calc-data-is*: *calculate-data-assumps-M p qs init-assumps*
= (*let q1* = *take* (*?len div 2*) *qs*; *left* = *calculate-data-assumps-M p q1 init-assumps*;
q2 = *drop* (*?len div 2*) *qs*; *right* = *calculate-data-assumps-M p q2 init-assumps*;
comb = *combine-systems-M p q1 left q2 right in*
reduce-system-M p (*fst comb*) (*snd comb*)
) **using** ∗ *calculate-data-assumps-M.simps*
by (*smt* (*z3*) *div-eq-0-iff bot-nat-0.not-eq-extremum div-greater-zero-iff rel-simps*(*69*))

let *?q1* = *take* (*?len div 2*) *qs*
let *?left* = *calculate-data-assumps-M p ?q1 init-assumps*
let *?q2* = *drop* (*?len div 2*) *qs*
let *?right* = *calculate-data-assumps-M p ?q2 init-assumps*
let *?comb* = *combine-systems-M p ?q1 ?left ?q2 ?right*
have *calc-data-is2*: *calculate-data-assumps-M p qs init-assumps*
= *reduce-system-M p* (*fst ?comb*) (*snd ?comb*) **using** *calc-data-is*
unfolding *Let-def*
by *auto*
have *length ?q1* < *?len* **using** ∗
by *auto*
then have ∃ (*assumps*, *mat-eq*) ∈ *set ?left*.
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *less.hyps*[*of ?q1 init-assumps val p*]
less.prems **by** *auto*
then obtain *assumps1 mat-eq1* **where** *assumps1*:
(*assumps1*, *mat-eq1*) ∈ *set ?left*
(∀ (*p*,*n*) ∈ *set assumps1*. *satisfies-evaluation val p n*)
by *blast*

have *length ?q2 < ?len* **using** ∗
by *auto*
then have ∃ (*assumps*, *mat-eq*) ∈ *set ?right*.
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *less.hyps*[*of ?q2 init-assumps val p*]
less.prems **by** *auto*
then obtain *assumps2 mat-eq2* **where** *assumps2*:
(*assumps2*, *mat-eq2*) ∈ *set ?right*
(∀ (*p*,*n*) ∈ *set assumps2*. *satisfies-evaluation val p n*)
by *blast*
have ∃ (*assumps*, *mat-eq*) ∈ *set* (*snd ?comb*).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *combine-systems-M-complete assumps1 assumps2*
by *auto*
then obtain *assumps-inbtw mat-eq-inbtw* **where**
(*assumps-inbtw*, *mat-eq-inbtw*) ∈ *set* (*snd ?comb*)
(∀ (*p*,*n*) ∈ *set assumps-inbtw*. *satisfies-evaluation val p n*)
by *blast*
then have ∃ (*assumps*, *mat-eq*) ∈ *set* (*reduce-system-M p* (*fst ?comb*) (*snd ?comb*)).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *reduce-system-M-complete*[*of assumps-inbtw val mat-eq-inbtw snd ?comb p fst ?comb*]
by *fastforce*
then have ∃ (*assumps*, *mat-eq*) ∈ *set* (*calculate-data-assumps-M p qs init-assumps*).
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *calc-data-is2*
by *presburger*
}
ultimately show *?case*
using ‹*length qs = 0* ∨ *length qs = 1* ∨ *1 < length qs*› **by** *fastforce*
qed

fun *extract-signs-single*:: *assumps* × *matrix-equation* ⇒ (*assumps* × *rat list list*)
where *extract-signs-single* (*assumps*, *mat-eq*) = (*assumps*, *snd* (*snd mat-eq*))

lemma *extract-signs-alt-char*:
shows *extract-signs qs = map extract-signs-single qs*
proof (*induct qs*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a qs*)
then show *?case*
using *extract-signs.simps extract-signs-single.simps*
by (*smt* (*verit*, *ccfv-threshold*) *list.map*(*2*) *snd-conv split-conv surj-pair*)
qed

lemma *get-all-valuations-helper*:

assumes (*assumps*, *mat-eq*) ∈ *set ell*
assumes *extract-signs-single* (*assumps*, *mat-eq*) = (*assumps*, *signs*)
shows (*assumps*, *signs*) ∈ *set* (*extract-signs ell*)
proof −
have *extract-signs ell* = *map extract-signs-single ell*
using *extract-signs-alt-char*
by *metis*
then show *?thesis* **using** *assms image-eqI*
by (*metis list.set-map*)
qed

lemma *get-all-valuations-alt*:
assumes ⋀*p n*. (*p*,*n*) ∈ *set init-assumps* ⟹ *satisfies-evaluation val p n*
shows ∃(*assumps*, *signs*) ∈ *set* (*sign-determination-inner qs init-assumps*).
(∀ *p n*. (*p*,*n*) ∈ *set assumps* ⟶ *satisfies-evaluation val p n*)
proof − **obtain** *branch-gen* **where** *branch-gen-prop*:
branch-gen ∈ *set* (*lc-assump-generation-list qs init-assumps*)
set (*fst branch-gen*) ⊆ *set* (*init-assumps*) ∪ *set*
(*map* (λ*x*. (*x*, *mpoly-sign val x*)) (*coeffs-list qs*))
using *assms lc-assump-generation-list-valuation*
by *blast*
then have *branch-gen*: ⋀*p n*. (*p*,*n*) ∈ *set* (*fst branch-gen*) ⟹ *satisfies-evaluation val p n*
using *lc-assump-generation-valuation-satisfies-eval*
by (*meson UnE assms in-mono*)
let *?poly-p-branch* = *poly-p-in-branch branch-gen*
let *?pos-limit-branch* = *fst* (*limit-points-on-branch branch-gen*)
let *?neg-limit-branch* = *snd* (*limit-points-on-branch branch-gen*)
let *?calculate-data-branch* = *extract-signs* (*calculate-data-assumps-M ?poly-p-branch* (*snd branch-gen*) (*fst branch-gen*))
have *lim-points*: *limit-points-on-branch branch-gen* = (*?pos-limit-branch*, *?neg-limit-branch*)
by *auto*
have *set* (*let poly-p-branch* = *poly-p-in-branch branch-gen*;
(*pos-limit-branch*, *neg-limit-branch*) = *limit-points-on-branch branch-gen*;
calculate-data-branch = *extract-signs* (*calculate-data-assumps-M poly-p-branch* (*snd branch-gen*) (*fst branch-gen*))
in map (λ(*a*, *signs*). (*a*, *pos-limit-branch*#*neg-limit-branch*#*signs*)) *calculate-data-branch*)
⊆ *set* (*sign-determination-inner qs init-assumps*)
using *branch-gen-prop*(*1*) *sign-determination-inner.simps* **by** *auto*
then have *in-signdet*: *set* (*map* (λ(*a*, *signs*). (*a*, *?pos-limit-branch*#*?neg-limit-branch*#*signs*)) *?calculate-data-branch*)
⊆ *set* (*sign-determination-inner qs init-assumps*)
using *lim-points* **unfolding** *Let-def*
proof −
assume *set* (*case limit-points-on-branch branch-gen of* (*pos-limit-branch*, *neg-limit-branch*) ⇒ *map* (λ(*a*, *signs*). (*a*, *pos-limit-branch* # *neg-limit-branch* # *signs*)) (*extract-signs* (*calculate-data-assumps-M* (*poly-p-in-branch branch-gen*) (*snd branch-gen*) (*fst branch-gen*)))) ⊆ *set* (*sign-determination-inner qs init-assumps*)

then show *?thesis*
by (*simp add*: *split-def*)
qed
obtain *assumps mat-eq* **where** *assumps-mat-prop*:
(*assumps*, *mat-eq*) ∈ *set* (*calculate-data-assumps-M ?poly-p-branch* (*snd branch-gen*) (*fst branch-gen*))
(∀ (*p*,*n*) ∈ *set assumps*. *satisfies-evaluation val p n*)
using *get-all-valuations-calculate-data-M branch-gen*
by (*smt* (*verit*, *del-insts*) *prod.exhaust-sel split-def*)
then obtain *m subsets signs* **where** *mat-eq-is*: *mat-eq* = (*m*, (*subsets*, *signs*))
using *prod-cases3* **by** *blast*
then have *pull-out*: *extract-signs-single* (*assumps*, *mat-eq*) = (*assumps*, *signs*)
using *extract-signs-single.simps* **by** *auto*
have *?calculate-data-branch* = (*map extract-signs-single*
(*calculate-data-assumps-M* (*poly-p-in-branch branch-gen*)
(*snd branch-gen*) (*fst branch-gen*)))
using *extract-signs-alt-char* **by** *auto*
then have (*assumps*, *signs*) ∈ *set ?calculate-data-branch*
using *assumps-mat-prop*(*1*) *pull-out get-all-valuations-helper*
by *blast*
then have (*assumps*, *?pos-limit-branch*#*?neg-limit-branch*#*signs*) ∈
set (*sign-determination-inner qs init-assumps*)
using *in-signdet* **by** *auto*
then show *?thesis*
using *assumps-mat-prop*(*2*)
by *blast*
qed

lemma *get-all-valuations*:
assumes ⋀*p n*. (*p*,*n*) ∈ *set init-assumps* ⟹ *satisfies-evaluation val p n*
obtains *assumps signs* **where** (*assumps*, *signs*) ∈ *set* (*sign-determination-inner qs init-assumps*)
⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation val p n*
using *assms get-all-valuations-alt*
by (*metis* (*no-types*, *lifting*) *case-prodE*)

17.11 Correctness of elim forall and elim exist

lemma *subset-zip-is-subset*:
assumes *set qs1* ⊆ *set qs*
assumes *signs* = *map* (*mpoly-sign val*) *qs*
assumes *signs1* = *map* (*mpoly-sign val*) *qs1*
shows *subset*: *set* (*zip qs1 signs1*) ⊆ *set* (*zip qs signs*)
proof *clarsimp*
fix *a b*
assume ∗: (*a*, *b*) ∈ *set* (*zip qs1 signs1*)
then have *a* ∈ *set qs1*
by (*meson set-zip-leftD*)
then have *a-in-qs*: *a* ∈ *set qs*

```
    using assms by auto
  have ⋀ba. set qs1 ⊆ set qs ⟹
        signs = map (mpoly-sign val) qs ⟹
        signs1 = map (mpoly-sign val) qs1 ⟹
        zip qs1 (map (mpoly-sign val) qs1) =
        map2 (λx y. (x, mpoly-sign val y)) qs1 qs1 ⟹
        (a, ba) ∈ set (zip qs1 qs1) ⟹
        b = mpoly-sign val ba ⟹ mpoly-sign val ba = mpoly-sign val a
     by (simp add: zip-same)
  then have b-is: b = mpoly-sign val a
    using ∗ assms zip-map2[of qs1 mpoly-sign val qs1]
    by (auto)
  have (a, mpoly-sign val a) ∈ set (map (λ(x,y).(x, mpoly-sign val y)) (zip qs qs))
    using a-in-qs zip-same[of a a qs] by auto
  then have (a, mpoly-sign val a) ∈ set (map2 (λx y. (x, mpoly-sign val y)) qs qs)
    by auto
  then show (a, b) ∈ set (zip qs signs)
    using b-is a-in-qs assms zip-map2[of qs mpoly-sign val qs]
    using assms(1) by presburger
qed

lemma extract-polys-subset:
  assumes signs = map (mpoly-sign val) qs
  assumes signs1 = map (mpoly-sign val) qs1
  assumes set qs1 ⊆ set qs
  assumes Some w = lookup-sem-M F (zip qs1 signs1)
  shows lookup-sem-M F (zip qs signs) = lookup-sem-M F (zip qs1 signs1)
  using assms
proof (induct F arbitrary: w)
  case TrueF
  then show ?case by auto
next
  case FalseF
  then show ?case by auto
next
  case (Atom x)
  have subset: set (zip qs1 signs1) ⊆ set (zip qs signs)
    using subset-zip-is-subset Atom.prems by auto
  show ?case
  proof (cases x)
    case (Less x1)
    then obtain i where i-prop: lookup-assump-aux x1 (zip qs1 signs1) = Some i
      using Atom.prems lookup-sem-M.simps
      by (metis lookup-assump-aux-eo option.simps(3) option.simps(4))
    have i-is: (x1, i) ∈ set (zip qs1 signs1)
      using i-prop lookup-assump-means-inset[of x1 (zip qs1 signs1) i]
      by auto
    then have (x1, i) ∈ set (zip qs signs)
      using subset by auto
```

then obtain *i1* **where** *lookup-assump-aux x1 (zip qs signs) = Some i1*
using *inset-means-lookup-assump-some[of x1 i (zip qs signs)]*
by *meson*
then have *i1-is*: *(x1, i1) ∈ set (zip qs signs)*
using *lookup-assump-means-inset[of x1 (zip qs signs) i1]*
by *auto*
have *⋀b. signs1 = map (mpoly-sign val) qs1 ⟹*
zip qs1 (map (mpoly-sign val) qs1) =
map2 (λx y. (x, mpoly-sign val y)) qs1 qs1 ⟹
(x1, b) ∈ set (zip qs1 qs1) ⟹
i = mpoly-sign val b ⟹ mpoly-sign val b = mpoly-sign val x1
by *(simp add: zip-same)*
then have *i-sign :i = mpoly-sign val x1*
using *i-is Atom.prems(2) zip-map2[of qs1 mpoly-sign val qs1]*
by *(auto)*
have *⋀b. signs = map (mpoly-sign val) qs ⟹*
zip qs (map (mpoly-sign val) qs) =
map2 (λx y. (x, mpoly-sign val y)) qs qs ⟹
(x1, b) ∈ set (zip qs qs) ⟹
i1 = mpoly-sign val b ⟹ mpoly-sign val b = mpoly-sign val x1
by *(simp add: zip-same)*
then have *i1-sign*: *i1 = mpoly-sign val x1*
using *i1-is Atom.prems(1) zip-map2[of qs mpoly-sign val qs]*
by *(auto)*
have *Sturm-Tarski.sign i1 = Sturm-Tarski.sign i*
using *i-sign i1-sign*
by *blast*
then show *?thesis* **using** *Atom.prems i-prop lookup-sem-M.simps*
using *Less ‹lookup-assump-aux x1 (zip qs signs) = Some i1› i1-sign i-sign*
by *presburger*
next
case *(Eq x1)*
then obtain *i* **where** *i-prop*: *lookup-assump-aux x1 (zip qs1 signs1) = Some i*
using *Atom.prems lookup-sem-M.simps*
by *(metis lookup-assump-aux-eo option.simps(3) option.simps(4))*
have *i-is*: *(x1, i) ∈ set (zip qs1 signs1)*
using *i-prop lookup-assump-means-inset[of x1 (zip qs1 signs1) i]*
by *auto*
then have *(x1, i) ∈ set (zip qs signs)*
using *subset* **by** *auto*
then obtain *i1* **where** *lookup-assump-aux x1 (zip qs signs) = Some i1*
by *(meson inset-means-lookup-assump-some)*
then have *i1-is*: *(x1, i1) ∈ set (zip qs signs)*
using *lookup-assump-means-inset[of x1 (zip qs signs) i1]*
by *auto*
have *⋀b. signs1 = map (mpoly-sign val) qs1 ⟹*
zip qs1 (map (mpoly-sign val) qs1) =
map2 (λx y. (x, mpoly-sign val y)) qs1 qs1 ⟹
(x1, b) ∈ set (zip qs1 qs1) ⟹

i = mpoly-sign val b ⟹ mpoly-sign val b = mpoly-sign val x1
by (*simp add*: *zip-same*)
then have *i-sign* :*i = mpoly-sign val x1*
using *i-is Atom.prems*(*2*) *zip-map2*[*of qs1 mpoly-sign val qs1*]
by (*auto*)
have ⋀*b*. *signs = map* (*mpoly-sign val*) *qs ⟹*
zip qs (*map* (*mpoly-sign val*) *qs*) =
map2 (λ*x y*. (*x*, *mpoly-sign val y*)) *qs qs ⟹*
(*x1*, *b*) ∈ *set* (*zip qs qs*) ⟹
i1 = mpoly-sign val b ⟹ mpoly-sign val b = mpoly-sign val x1
by (*simp add*: *zip-same*)
then have *i1-sign*: *i1 = mpoly-sign val x1*
using *i1-is Atom.prems*(*1*) *zip-map2*[*of qs mpoly-sign val qs*]
by (*auto*)
have *Sturm-Tarski.sign i1 = Sturm-Tarski.sign i*
using *i-sign i1-sign*
by *blast*
then show *?thesis* **using** *Atom.prems i-prop lookup-sem-M.simps*
using *Eq* ‹*lookup-assump-aux x1* (*zip qs signs*) = *Some i1*› *i1-sign i-sign* **by** *presburger*
next
case (*Leq x1*)
then obtain *i* **where** *i-prop*: *lookup-assump-aux x1* (*zip qs1 signs1*) = *Some i*
using *Atom.prems lookup-sem-M.simps*
by (*metis lookup-assump-aux-eo option.simps*(*3*) *option.simps*(*4*))
have *i-is*: (*x1*, *i*) ∈ *set* (*zip qs1 signs1*)
using *i-prop lookup-assump-means-inset*[*of x1* (*zip qs1 signs1*) *i*]
by *auto*
then have (*x1*, *i*) ∈ *set* (*zip qs signs*)
using *subset* **by** *auto*
then obtain *i1* **where** *lookup-assump-aux x1* (*zip qs signs*) = *Some i1*
by (*meson inset-means-lookup-assump-some*)
then have *i1-is*: (*x1*, *i1*) ∈ *set* (*zip qs signs*)
using *lookup-assump-means-inset*[*of x1* (*zip qs signs*) *i1*]
by *auto*
have ⋀*b*. *signs1 = map* (*mpoly-sign val*) *qs1 ⟹*
zip qs1 (*map* (*mpoly-sign val*) *qs1*) =
map2 (λ*x y*. (*x*, *mpoly-sign val y*)) *qs1 qs1 ⟹*
(*x1*, *b*) ∈ *set* (*zip qs1 qs1*) ⟹
i = mpoly-sign val b ⟹ mpoly-sign val b = mpoly-sign val x1
by (*simp add*: *zip-same*)
then have *i-sign* :*i = mpoly-sign val x1*
using *i-is Atom.prems*(*2*) *zip-map2*[*of qs1 mpoly-sign val qs1*]
by (*auto*)
have ⋀*b*. *signs = map* (*mpoly-sign val*) *qs ⟹*
zip qs (*map* (*mpoly-sign val*) *qs*) =
map2 (λ*x y*. (*x*, *mpoly-sign val y*)) *qs qs ⟹*
(*x1*, *b*) ∈ *set* (*zip qs qs*) ⟹
i1 = mpoly-sign val b ⟹ mpoly-sign val b = mpoly-sign val x1

by (*simp add*: *zip-same*)
then have *i1-sign*: *i1* = *mpoly-sign val x1*
using *i1-is* *Atom.prems*(*1*) *zip-map2*[*of qs mpoly-sign val qs*]
by (*auto*)
have *Sturm-Tarski.sign i1* = *Sturm-Tarski.sign i*
using *i-sign i1-sign*
by *blast*
then show *?thesis* **using** *Atom.prems i-prop lookup-sem-M.simps*
using *Leq* ‹*lookup-assump-aux x1* (*zip qs signs*) = *Some i1*› *i1-sign i-sign* **by** *presburger*
next
case (*Neq x1*)
then obtain *i* **where** *i-prop*: *lookup-assump-aux x1* (*zip qs1 signs1*) = *Some i*
using *Atom.prems lookup-sem-M.simps*
by (*metis lookup-assump-aux-eo option.simps*(*3*) *option.simps*(*4*))
have *i-is*: (*x1*, *i*) ∈ *set* (*zip qs1 signs1*)
using *i-prop lookup-assump-means-inset*[*of x1* (*zip qs1 signs1*) *i*]
by *auto*
then have (*x1*, *i*) ∈ *set* (*zip qs signs*)
using *subset* **by** *auto*
then obtain *i1* **where** *lookup-assump-aux x1* (*zip qs signs*) = *Some i1*
by (*meson inset-means-lookup-assump-some*)
then have *i1-is*: (*x1*, *i1*) ∈ *set* (*zip qs signs*)
using *lookup-assump-means-inset*[*of x1* (*zip qs signs*) *i1*]
by *auto*
have ⋀*b*. *signs1* = *map* (*mpoly-sign val*) *qs1* ⟹
zip qs1 (*map* (*mpoly-sign val*) *qs1*) =
map2 (λ*x y*. (*x*, *mpoly-sign val y*)) *qs1 qs1* ⟹
(*x1*, *b*) ∈ *set* (*zip qs1 qs1*) ⟹
i = *mpoly-sign val b* ⟹ *mpoly-sign val b* = *mpoly-sign val x1*
by (*simp add*: *zip-same*)
then have *i-sign* :*i* = *mpoly-sign val x1*
using *i-is* *Atom.prems*(*2*) *zip-map2*[*of qs1 mpoly-sign val qs1*]
by (*auto*)
have ⋀*b*. *signs* = *map* (*mpoly-sign val*) *qs* ⟹
zip qs (*map* (*mpoly-sign val*) *qs*) =
map2 (λ*x y*. (*x*, *mpoly-sign val y*)) *qs qs* ⟹
(*x1*, *b*) ∈ *set* (*zip qs qs*) ⟹
i1 = *mpoly-sign val b* ⟹ *mpoly-sign val b* = *mpoly-sign val x1*
by (*simp add*: *zip-same*)
then have *i1-sign*: *i1* = *mpoly-sign val x1*
using *i1-is* *Atom.prems*(*1*) *zip-map2*[*of qs mpoly-sign val qs*]
by (*auto*)
have *Sturm-Tarski.sign i1* = *Sturm-Tarski.sign i*
using *i-sign i1-sign*
by *blast*
then show *?thesis* **using** *Atom.prems i-prop lookup-sem-M.simps*
using *Neq* ‹*lookup-assump-aux x1* (*zip qs signs*) = *Some i1*› *i1-sign i-sign* **by** *presburger*

```
  qed
next
  case (And F1 F2)
  let ?sub-ell = (zip qs1 signs1)
  have case-some: lookup-sem-M (fm.And F1 F2) ?sub-ell = (case (lookup-sem-M
F1 ?sub-ell, lookup-sem-M F2 ?sub-ell)
      of (Some i, Some j) ⇒ Some (i ∧ j)
      | - ⇒ None)
    using lookup-sem-M.simps by simp
  have e1: ∃ w1. lookup-sem-M F1 ?sub-ell = Some w1
    using case-some And.prems(4)
    using proper-interval-bool.elims(1) by fastforce
  have e2: ∃ w2. lookup-sem-M F2 ?sub-ell = Some w2
    using case-some And.prems(4)
    using proper-interval-bool.elims(1)
    by (smt (z3) option.case(1) option.simps(5) split-conv)
  then obtain w1 w2 where lookup-sem-M F1 ?sub-ell = Some w1
    lookup-sem-M F2 ?sub-ell = Some w2
    using e1 e2 by auto
  have ind1: lookup-sem-M F1 (zip qs signs) = lookup-sem-M F1 (zip qs1 signs1)
    using e1 And.hyps(1) And.prems(1−3) by auto
  have ind2: lookup-sem-M F2 (zip qs signs) = lookup-sem-M F2 (zip qs1 signs1)
    using e2 And.hyps(2) And.prems(1−3) by auto
  then show ?case  using lookup-sem-M.simps
      ind1 ind2
    by presburger
next
  case (Or F1 F2)
  let ?sub-ell = (zip qs1 signs1)
  have case-some: lookup-sem-M (fm.Or F1 F2) ?sub-ell = (case (lookup-sem-M
F1 ?sub-ell, lookup-sem-M F2 ?sub-ell)
      of (Some i, Some j) ⇒ Some (i ∨ j)
      | - ⇒ None)
    using lookup-sem-M.simps by simp
  have e1: ∃ w1. lookup-sem-M F1 ?sub-ell = Some w1
    using case-some Or.prems(4)
    using proper-interval-bool.elims(1) by fastforce
  have e2: ∃ w2. lookup-sem-M F2 ?sub-ell = Some w2
    using case-some Or.prems(4)
    using proper-interval-bool.elims(1)
    by (smt (z3) option.case(1) option.simps(5) split-conv)
  then obtain w1 w2 where lookup-sem-M F1 ?sub-ell = Some w1
    lookup-sem-M F2 ?sub-ell = Some w2
    using e1 e2 by auto
  have ind1: lookup-sem-M F1 (zip qs signs) = lookup-sem-M F1 (zip qs1 signs1)
    using e1 Or.hyps(1) Or.prems(1−3) by auto
  have ind2: lookup-sem-M F2 (zip qs signs) = lookup-sem-M F2 (zip qs1 signs1)
    using e2 Or.hyps(2) Or.prems(1−3) by auto
  then show ?case  using lookup-sem-M.simps
```

```
    ind1 ind2
   by presburger
next
 case (Neg F)
 then show ?case
   by (metis lookup-sem-M.simps(5) not-Some-eq option.case(1))
next
 case (ExQ F)
 then show ?case by auto
next
 case (AllQ F)
 then show ?case by auto
next
 case (ExN x1 F)
 then show ?case
  by (metis add-Suc-right le-Suc-eq' le-add-same-cancel1 lookup-sem-M.simps(10)
lookup-sem-M.simps(14))
next
 case (AllN x1 F)
 then show ?case
   by (metis lookup-sem-M.simps(11) lookup-sem-M.simps(15) zero-list.cases)
qed

lemma extract-polys-semantics:
 assumes qs = extract-polys F
 assumes signs = map (mpoly-sign val) qs
 assumes countQuantifiers F = 0
 shows Some (eval F val) = lookup-sem-M F (zip qs signs)
 using assms
proof (induct F arbitrary: qs signs)
 case TrueF
 then show ?case by auto
next
 case FalseF
 then show ?case
   by auto
next
 case (Atom x)
 then show ?case
 proof (cases x)
   case (Less x1)
   then have extract-polys (fm.Atom x) = [x1]
     using extract-polys.simps by auto
   then have qs-is: qs = [x1] using Atom.prems
     by auto
   then have signs-is: signs = [mpoly-sign val x1]
     using Atom.prems by auto
   then have zip-is: zip qs signs = [(x1, mpoly-sign val x1)]
     using qs-is by auto
```

```
    then have lookup-sem-is: lookup-sem-M (fm.Atom x) (zip qs signs) =
      (case (lookup-assump-aux x1 (zip qs signs)) of
     Some i ⇒ Some (i < 0)
    | - ⇒ None)using Less
      by auto
    have lookup-assump-aux x1 (zip qs signs) = Some (mpoly-sign val x1)
      using zip-is by auto
   then have lookup-is: lookup-sem-M (fm.Atom x) (zip qs signs) = Some ((mpoly-sign
val x1) < 0)
      using lookup-sem-is by auto
    have eval-is: eval (fm.Atom x) val = (insertion (nth-default 0 val) x1 < 0)
      using Less by auto
    have (mpoly-sign val x1) < 0 =  (insertion (nth-default 0 val) x1 < 0)
      unfolding mpoly-sign-def eval-mpoly-def Sturm-Tarski.sign-def
      by auto
    then show ?thesis using eval-is lookup-is
      by auto
  next
    case (Eq x1)
    then have extract-polys (fm.Atom x) = [x1]
      using extract-polys.simps by auto
    then have qs-is: qs = [x1] using Atom.prems
      by auto
    then have signs-is: signs = [mpoly-sign val x1]
      using Atom.prems by auto
    then have zip-is: zip qs signs = [(x1, mpoly-sign val x1)]
      using qs-is by auto
    then have lookup-sem-is: lookup-sem-M (fm.Atom x) (zip qs signs) =
      (case (lookup-assump-aux x1 (zip qs signs)) of
     Some i ⇒ Some (i = 0)
    | - ⇒ None)using Eq
      by auto
    have lookup-assump-aux x1 (zip qs signs) = Some (mpoly-sign val x1)
      using zip-is by auto
   then have lookup-is: lookup-sem-M (fm.Atom x) (zip qs signs) = Some ((mpoly-sign
val x1) = 0)
      using lookup-sem-is by auto
    have eval-is: eval (fm.Atom x) val = (insertion (nth-default 0 val) x1 = 0)
      using Eq by auto
    have (mpoly-sign val x1) = 0 =  (insertion (nth-default 0 val) x1 = 0)
      unfolding mpoly-sign-def eval-mpoly-def Sturm-Tarski.sign-def
      by auto
    then show ?thesis using eval-is lookup-is
      by auto
  next
    case (Leq x1)
    then have extract-polys (fm.Atom x) = [x1]
      using extract-polys.simps by auto
    then have qs-is: qs = [x1] using Atom.prems
```

by *auto*
then have *signs-is*: *signs* = [*mpoly-sign val x1*]
using *Atom.prems* **by** *auto*
then have *zip-is*: *zip qs signs* = [(*x1*, *mpoly-sign val x1*)]
using *qs-is* **by** *auto*
then have *lookup-sem-is*: *lookup-sem-M* (*fm.Atom x*) (*zip qs signs*) =
(*case* (*lookup-assump-aux x1* (*zip qs signs*)) *of*
Some i ⇒ *Some* (*i* ≤ *0*)
| - ⇒ *None*)**using** *Leq*
by *auto*
have *lookup-assump-aux x1* (*zip qs signs*) = *Some* (*mpoly-sign val x1*)
using *zip-is* **by** *auto*
then have *lookup-is*: *lookup-sem-M* (*fm.Atom x*) (*zip qs signs*) = *Some* ((*mpoly-sign val x1*) ≤ *0*)
using *lookup-sem-is* **by** *auto*
have *eval-is*: *eval* (*fm.Atom x*) *val* = (*insertion* (*nth-default 0 val*) *x1* ≤ *0*)
using *Leq* **by** *auto*
have (*mpoly-sign val x1*) ≤ *0* = (*insertion* (*nth-default 0 val*) *x1* ≤ *0*)
unfolding *mpoly-sign-def eval-mpoly-def Sturm-Tarski.sign-def*
by *auto*
then show *?thesis* **using** *eval-is lookup-is*
by *auto*
next
case (*Neq x1*)
then have *extract-polys* (*fm.Atom x*) = [*x1*]
using *extract-polys.simps* **by** *auto*
then have *qs-is*: *qs* = [*x1*] **using** *Atom.prems*
by *auto*
then have *signs-is*: *signs* = [*mpoly-sign val x1*]
using *Atom.prems* **by** *auto*
then have *zip-is*: *zip qs signs* = [(*x1*, *mpoly-sign val x1*)]
using *qs-is* **by** *auto*
then have *lookup-sem-is*: *lookup-sem-M* (*fm.Atom x*) (*zip qs signs*) =
(*case* (*lookup-assump-aux x1* (*zip qs signs*)) *of*
Some i ⇒ *Some* (*i* ≠ *0*)
| - ⇒ *None*)**using** *Neq*
by *auto*
have *lookup-assump-aux x1* (*zip qs signs*) = *Some* (*mpoly-sign val x1*)
using *zip-is* **by** *auto*
then have *lookup-is*: *lookup-sem-M* (*fm.Atom x*) (*zip qs signs*) = *Some* ((*mpoly-sign val x1*) ≠ *0*)
using *lookup-sem-is* **by** *auto*
have *eval-is*: *eval* (*fm.Atom x*) *val* = (*insertion* (*nth-default 0 val*) *x1* ≠ *0*)
using *Neq* **by** *auto*
have (*mpoly-sign val x1*) ≠ *0* = (*insertion* (*nth-default 0 val*) *x1* ≠ *0*)
unfolding *mpoly-sign-def eval-mpoly-def Sturm-Tarski.sign-def*
by *auto*
then show *?thesis* **using** *eval-is lookup-is*
by *auto*

qed
next
case (*And F1 F2*)
have *qs-is*: *qs* = (*extract-polys F1*)@(*extract-polys F2*)
using *And.prems*(*1*) *extract-polys.simps*
by *force*
then obtain *signs1 signs2* **where** *signs-prop*:
signs1 = *map* (*mpoly-sign val*) (*extract-polys F1*)
signs2 = *map* (*mpoly-sign val*) (*extract-polys F2*)
signs = *signs1* @ *signs2*
using *And.prems*(*2*) **by** *auto*
have *subset-f1*: *set* (*extract-polys F1*) ⊆ *set qs*
using *qs-is* **by** *auto*
have *subset-f2*: *set* (*extract-polys F2*) ⊆ *set qs*
using *qs-is* **by** *auto*
have *f1-free*: *countQuantifiers F1* = *0*
using *And.prems*(*3*)
by *auto*
have *f2-free*: *countQuantifiers F2* = *0*
using *And.prems*(*3*)
by *auto*
have *zip-is*: (*zip qs signs*) = (*zip* (*extract-polys F1*) *signs1*)@(*zip* (*extract-polys F2*) *signs2*)
using *qs-is signs-prop*(*3*)
by (*simp add*: *signs-prop*(*1*))
have *ind1*: *Some* (*eval F1 val*) = *lookup-sem-M F1* (*zip* (*extract-polys F1*) *signs1*)
using *And.hyps*(*1*) *signs-prop*(*1*) *f1-free* **by** *auto*
have *subset*: *set* (*zip* (*extract-polys F1*) *signs1*) ⊆ *set* (*zip qs signs*)
using *subset-zip-is-subset And.prems signs-prop*(*1*) **by** *auto*
then have *lookup1*: *lookup-sem-M F1* (*zip* (*extract-polys F1*) *signs1*) = *lookup-sem-M F1* (*zip qs signs*)
using *extract-polys-subset*[*of signs val qs signs1 extract-polys F1*] *ind1 subset-f1 signs-prop*(*1*) *qs-is And.prems*(*2*)
by *auto*
then have *restate-ind1*: *lookup-sem-M F1* (*zip qs signs*) = *Some* (*eval F1 val*)
using *ind1 lookup1*
by *auto*
have *ind2*: *Some* (*eval F2 val*) = *lookup-sem-M F2* (*zip* (*extract-polys F2*) *signs2*)
using *And.hyps*(*2*) *signs-prop*(*2*) *f2-free* **by** *auto*
then have *lookup2*: *lookup-sem-M F2* (*zip* (*extract-polys F2*) *signs2*) = *lookup-sem-M F2* (*zip qs signs*)
using *extract-polys-subset*[*of signs val qs signs2 extract-polys F2*] *ind2 subset-f2 signs-prop*(*2*) *And.prems*(*2*)
by *auto*
then have *restate-ind2*: *lookup-sem-M F2* (*zip qs signs*) = *Some* (*eval F2 val*)
using *ind2 lookup2*
by *auto*
show *?case* **using** *signs-prop*(*3*)
restate-ind1 restate-ind2

```
    qs-is zip-is lookup-sem-M.simps
   by simp
next
 case (Or F1 F2)
 have qs-is: qs = (extract-polys F1)@(extract-polys F2)
   using Or.prems(1) extract-polys.simps
   by force
 then obtain signs1 signs2 where signs-prop:
   signs1 = map (mpoly-sign val) (extract-polys F1)
   signs2 = map (mpoly-sign val) (extract-polys F2)
   signs = signs1 @ signs2
   using Or.prems(2) by auto
 have subset-f1: set (extract-polys F1) ⊆ set qs
   using qs-is by auto
 have subset-f2: set (extract-polys F2) ⊆ set qs
   using qs-is by auto
 have f1-free: countQuantifiers F1 = 0
   using Or.prems(3)
   by auto
 have f2-free: countQuantifiers F2 = 0
   using Or.prems(3)
   by auto
 have zip-is: (zip qs signs) = (zip (extract-polys F1) signs1)@(zip (extract-polys
F2) signs2)
   using qs-is signs-prop(3)
   by (simp add: signs-prop(1))
 have ind1: Some (eval F1 val) = lookup-sem-M F1 (zip (extract-polys F1) signs1)
   using Or.hyps(1) signs-prop(1) f1-free by auto
 have subset: set (zip (extract-polys F1) signs1) ⊆ set (zip qs signs)
   using subset-zip-is-subset Or.prems signs-prop(1) by auto
 then have lookup1: lookup-sem-M F1 (zip (extract-polys F1) signs1) = lookup-sem-M
F1 (zip qs signs)
   using extract-polys-subset[of signs val qs signs1 extract-polys F1] ind1 subset-f1
signs-prop(1) qs-is Or.prems(2)
   by auto
 then have restate-ind1: lookup-sem-M F1 (zip qs signs) = Some (eval F1 val)
   using ind1 lookup1
   by auto
 have ind2: Some (eval F2 val) = lookup-sem-M F2 (zip (extract-polys F2) signs2)
   using Or.hyps(2) signs-prop(2) f2-free by auto
 then have lookup2: lookup-sem-M F2 (zip (extract-polys F2) signs2) = lookup-sem-M
F2 (zip qs signs)
   using extract-polys-subset[of signs val qs signs2 extract-polys F2] ind2 subset-f2
signs-prop(2) Or.prems(2)
   by auto
 then have restate-ind2: lookup-sem-M F2 (zip qs signs) = Some (eval F2 val)
   using ind2 lookup2
   by auto
 show ?case using signs-prop(3)
```

```
      restate-ind1 restate-ind2
      qs-is zip-is lookup-sem-M.simps
    by simp
next
  case (Neg F)
  have qs-is: qs = (extract-polys F)
    using Neg.prems(1) extract-polys.simps
    by force
  have cq-zer: countQuantifiers F = 0
    using Neg.prems(3) by auto
  have Some (eval F val) = lookup-sem-M F (zip qs signs)
    using qs-is cq-zer Neg.hyps[of qs signs] Neg.prems(2)
    by auto
  then show ?case using lookup-sem-M.simps
    by (smt (verit, best) eval.simps(6) option.simps(5))
next
  case (ExQ F)
  have countQuantifiers (ExQ F) > 0
    by auto
  then show ?case using ExQ.prems(3) by auto
next
  case (AllQ F)
  have countQuantifiers (AllQ F) > 0
    by auto
  then show ?case using AllQ.prems(3) by auto
next
  case (ExN x1 F)
  {assume *: x1 = 0
    then have h1: eval (ExN x1 F) val = eval F val
      by auto
    have h2: lookup-sem-M (ExN x1 F) (zip qs signs)
       = lookup-sem-M F (zip qs signs)
      using * by auto
    have qs-is: qs = extract-polys F using * ExN.prems(1)
       extract-polys.simps by auto
    have countQuantifiers F = 0
      using ExN.prems(3) by auto
    then have Some (eval (ExN x1 F) val) =
      lookup-sem-M (ExN x1 F) (zip qs signs)
      using qs-is h1 h2 ExN.hyps[of qs signs] ExN.prems(2) by auto
  }
  moreover {assume *: x1 > 0
    then have countQuantifiers (ExN x1 F) > 0
      by auto
    then have Some (eval (ExN x1 F) val) =
      lookup-sem-M (ExN x1 F) (zip qs signs)
      using ExN.prems(3) by auto
  }
  ultimately show ?case
```

```
    by fastforce
next
  case (AllN x1 F)
  {assume *: x1 = 0
    then have h1: eval (AllN x1 F) val = eval F val
      by auto
    have h2: lookup-sem-M (AllN x1 F) (zip qs signs)
        = lookup-sem-M F (zip qs signs)
      using * by auto
    have qs-is: qs = extract-polys F using * AllN.prems(1)
        extract-polys.simps by auto
    have countQuantifiers F = 0
      using AllN.prems(3) by auto
    then have Some (eval (AllN x1 F) val) =
      lookup-sem-M (AllN x1 F) (zip qs signs)
      using qs-is h1 h2 AllN.hyps[of qs signs] AllN.prems(2) by auto
  }
  moreover {assume *: x1 > 0
    then have countQuantifiers (AllN x1 F) > 0
      by auto
    then have Some (eval (AllN x1 F) val) =
      lookup-sem-M (AllN x1 F) (zip qs signs)
      using AllN.prems(3) by auto
  }
  ultimately show ?case
    by fastforce
qed

lemma create-disjunction-eval:
  assumes eval (create-disjunction data) xs
  shows ∃ a ∈ set data. (eval (assump-to-atom-fm (fst a)) xs)
  using assms
proof (induct data)
  case Nil
  then show ?case by auto
next
  case (Cons a data)
  then show ?case
   by (metis create-disjunction.elims eval-Or fst-conv list.set-intros(1) list.set-intros(2)
list.simps(1) list.simps(3))
qed

lemma assump-to-atom-fm-conjunction:
  assumes eval (assump-to-atom-fm assumps) xs
  shows (p, n) ∈ set assumps ⟹ satisfies-evaluation xs p n
  using assms
proof (induct assumps)
  case Nil
  then show ?case by auto
```

```
next
  case (Cons a assumps)
  then have eval-prop: eval (assump-to-atom-fm assumps) xs
    eval (Atom (assump-to-atom ((fst a), (snd a)))) xs
     apply (metis assump-to-atom-fm.simps(2) eval.simps(4) old.prod.exhaust)
   by (metis Cons.prems(2) assump-to-atom-fm.simps(2) eval.simps(4) prod.exhaust-sel)
  {assume * : (p, n) = a
   have aEval (if n = 0 then atom.Eq p else if n < 0 then Less p else Less (− p))
    xs ⟹ Sturm-Tarski.sign (eval-mpoly xs p) = Sturm-Tarski.sign n
   proof −
    assume eval-h: aEval (if n = 0 then atom.Eq p else if n < 0 then Less p else
Less (− p))
    xs
    {assume **: n = 0
     then have Sturm-Tarski.sign (eval-mpoly xs p) = Sturm-Tarski.sign n
      using eval-h unfolding eval-mpoly-def by auto
    } moreover
    {assume **: n > 0
     then have Sturm-Tarski.sign (eval-mpoly xs p) = Sturm-Tarski.sign n
      using eval-h unfolding eval-mpoly-def by auto
    } moreover
    {assume **: n < 0
     then have Sturm-Tarski.sign (eval-mpoly xs p) = Sturm-Tarski.sign n
      using eval-h unfolding eval-mpoly-def by auto
    }
    ultimately show Sturm-Tarski.sign (eval-mpoly xs p) = Sturm-Tarski.sign
n
      using linorder-cases by blast
   qed
   then have satisfies-evaluation xs p n
    using eval-prop(2) * unfolding satisfies-evaluation-def
    by auto
  }
  moreover {assume *: (p, n) ∈ set assumps
   then have satisfies-evaluation xs p n
    using eval-prop(1) Cons.hyps by auto
  }
  ultimately show ?case using Cons.prems(1) by auto
qed

lemma eval-elim-forall-correct1:
  fixes F:: atom fm
  assumes *: countQuantifiers F = 0
  assumes eval (elim-forall F) xs
  shows (eval F (x#xs))
proof −
  let ?qs = extract-polys F
  let ?univ-qs = univariate-in ?qs 0
  let ?reindexed-univ-qs = map (map-poly (lowerPoly 0 1)) ?univ-qs
```

let *?data = sign-determination-inner ?reindexed-univ-qs* []
let *?new-data = filter* (λ(*assumps*, *signs-list*).
list-all (λ *signs*.
let paired-signs = zip ?qs signs in
lookup-sem-M F paired-signs = (*Some True*))
signs-list
) *?data*
have *elim-forall F = create-disjunction ?new-data*
unfolding *elim-forall.simps Let-def*
by *fastforce*
then have *eval* (*create-disjunction ?new-data*) *xs*
using *assms*
by *presburger*
then obtain *a* **where** *a-prop1*: *a* ∈ *set ?new-data*
(*eval* (*assump-to-atom-fm* (*fst a*)) *xs*)
using *create-disjunction-eval*
by *blast*
then have *a-prop2*: *a* ∈ *set ?data*
(*list-all* (λ *signs*.
let paired-signs = zip ?qs signs in
lookup-sem-M F paired-signs = (*Some True*))
(*snd a*))
apply (*smt* (*verit*, *best*) *mem-Collect-eq set-filter*)
by (*smt* (*verit*, *del-insts*) *a-prop1*(*1*) *mem-Collect-eq set-filter split-def*)
have *a-in*: (*fst a*, *snd a*) ∈ *set* (*sign-determination-inner ?reindexed-univ-qs* [])
using *a-prop2*(*1*) **by** *auto*
have ⋀*p n*. (*p*,*n*) ∈ *set* (*fst a*) ⟹ *satisfies-evaluation xs p n*
using *a-prop1*(*2*) *assump-to-atom-fm-conjunction*
by *blast*
from *sign-determination-inner-gives-noncomp-signs-at-roots*[*OF a-in this*]
have *set* (*snd a*) =
consistent-sign-vectors-R (*map* (*eval-mpoly-poly xs*) *?reindexed-univ-qs*) *UNIV*
by *auto*
then have *csv*: (*consistent-sign-vec* (*map* (*eval-mpoly-poly xs*) *?reindexed-univ-qs*))
x ∈ *set* (*snd a*)
unfolding *consistent-sign-vectors-R-def* **by** *auto*

have *map-rel1*: *map* (*Sturm-Tarski.sign*) (*map* (λ*p*. *poly p x*) (*map* (*eval-mpoly-poly xs*) (*map* (*map-poly* (*lowerPoly 0 1*)) (*univariate-in* (*extract-polys F*) *0*))))
= (*consistent-sign-vec* (*map* (*eval-mpoly-poly xs*) *?reindexed-univ-qs*)) *x*
unfolding *consistent-sign-vec-def Sturm-Tarski.sign-def*
by *auto*
then have *map-rel2*: *map* (*eval-mpoly* (*x # xs*)) (*extract-polys F*) =
map (λ*p*. *poly p x*) (*map* (*eval-mpoly-poly xs*) (*map* (*map-poly* (*lowerPoly 0 1*)) (*univariate-in* (*extract-polys F*) *0*)))
using *reindexed-univ-qs-eval*[*of* - (*extract-polys F*)] **by** *auto*
then have *map-rel3*: *map Sturm-Tarski.sign* (*map* (*eval-mpoly* (*x # xs*)) (*extract-polys F*)) =
map (*Sturm-Tarski.sign*) (*map* (λ*p*. *poly p x*) (*map* (*eval-mpoly-poly xs*) (*map*

(*map-poly* (*lowerPoly 0 1*)) (*univariate-in* (*extract-polys F*) *0*))))
by *auto*
have *map-rel4*: *map Sturm-Tarski.sign* (*map* (*eval-mpoly* (*x # xs*)) (*extract-polys F*)) = *map* (*mpoly-sign* (*x#xs*)) *?qs*
unfolding *mpoly-sign-def* **by** *auto*
have *map* (*mpoly-sign* (*x#xs*)) *?qs* =(*consistent-sign-vec* (*map* (*eval-mpoly-poly xs*) *?reindexed-univ-qs*)) *x*
using *map-rel1 map-rel2 map-rel3 map-rel4*
by (*metis list.inj-map-strong of-rat-hom.injectivity*)

then obtain *signs* **where** *signs-prop*: *signs* ∈ *set* (*snd a*)
signs = *map* (*mpoly-sign* (*x#xs*)) *?qs*
using *csv* **by** *auto*
then have *lookup-sem-match*: *Some* (*eval F* (*x#xs*)) = *lookup-sem-M F* (*zip ?qs signs*)
using ∗ *extract-polys-semantics* **by** *auto*
have *lookup-sem-M F* (*zip ?qs signs*) = *Some* (*True*)
using *a-prop2*(*2*) *signs-prop*(*1*) **unfolding** *Let-def*
by (*smt* (*verit*, *ccfv-SIG*) *lookup-sem-match a-prop2*(*2*) *list.pred-mono-strong mem-Collect-eq option.simps*(*1*) *set-filter subset-code*(*1*) *subset-set-code*)
then show *?thesis*
using *lookup-sem-match* **by** *auto*
qed

lemma *assump-to-atom-fm-eval*:
assumes ⋀*p n*. (*p*,*n*) ∈ *set assumps* ⟹ *satisfies-evaluation xs p n*
shows (*eval* (*assump-to-atom-fm assumps*) *xs*)
using *assms*
proof (*induct assumps*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a assumps*)
then have *h1*: *eval* (*assump-to-atom-fm assumps*) *xs*
by *simp*
have *sat-eval*: *satisfies-evaluation xs* (*fst a*) (*snd a*)
using *Cons.prems* **by** *auto*
have *h2*: *eval* (*Atom* (*assump-to-atom* ((*fst a*), (*snd a*)))) *xs*
proof −
{assume ∗: *snd a* = *0*
then have *eval* (*Atom* (*assump-to-atom* ((*fst a*), (*snd a*)))) *xs*
using *sat-eval* **unfolding** *satisfies-evaluation-def eval-mpoly-def Sturm-Tarski.sign-def*
by (*smt* (*verit*, *del-insts*) *aEval.simps*(*1*) *assump-to-atom.simps eval.simps*(*1*) *less-numeral-extra*(*3*) *of-int-hom.eq-iff*)

} moreover
{assume ∗: *0* < *snd a*
then have (*eval-mpoly xs* (*fst a*)) > *0*

```
      using sat-eval unfolding satisfies-evaluation-def Sturm-Tarski.sign-def
      by (smt (verit, del-insts) of-int-hom.eq-iff)

    then have aEval (Less (−(fst a))) xs
      using ∗ unfolding eval-mpoly-def by auto
    then have  aEval (assump-to-atom a) xs
      using ∗ assump-to-atom.simps[of fst a snd a] by auto
    then have eval (Atom (assump-to-atom ((fst a), (snd a)))) xs
      by auto
  } moreover
  {assume ∗: 0 > snd a
    then have (eval-mpoly xs (fst a)) < 0
      using sat-eval unfolding satisfies-evaluation-def Sturm-Tarski.sign-def
      by (smt (z3) of-int-hom.eq-iff sign-simps(1) sign-simps(3))

    then have aEval (Less ((fst a))) xs
      using ∗ unfolding eval-mpoly-def by auto
    then have  aEval (assump-to-atom a) xs
      using ∗ assump-to-atom.simps[of fst a snd a] by auto
    then have eval (Atom (assump-to-atom ((fst a), (snd a)))) xs
      by auto
  }
  ultimately show ?thesis
    by linarith
 qed
 then show ?case
  using h1 h2
  by (metis assump-to-atom-fm.simps(2) eval.simps(4) prod.exhaust-sel)
qed

lemma create-disjunction-true:
 assumes (assumps, signs) ∈ set data
 assumes  (eval (assump-to-atom-fm assumps) xs)
 shows eval (create-disjunction data) xs
 using assms
proof (induct data)
 case Nil
 then show ?case by auto
next
 case (Cons a data)
 then show ?case
  by (metis create-disjunction.simps(2) eval.simps(5) prod.exhaust-sel set-ConsD)

qed

lemma eval-elim-forall-correct2:
 fixes F:: atom fm
 assumes countQuantifiers F = 0
 assumes (∀ x. (eval F (x#xs)))
```

```
  shows eval (elim-forall F) xs
proof −
  let ?qs = extract-polys F
  let ?univ-qs = univariate-in ?qs 0
  let ?reindexed-univ-qs = map (map-poly (lowerPoly 0 1)) ?univ-qs
  let ?data = sign-determination-inner ?reindexed-univ-qs []
  let ?new-data = filter (λ(assumps, signs-list).
      list-all (λ signs.
      let paired-signs = zip ?qs signs in
        lookup-sem-M F paired-signs = (Some True))
      signs-list
      ) ?data
  have h1: elim-forall F = create-disjunction ?new-data
    unfolding elim-forall.simps Let-def
    by fastforce
  have ⋀p n. (p,n) ∈ set [] ⟹ satisfies-evaluation xs p n
    by auto

  then obtain assumps signs where assumps-signs: (assumps, signs) ∈ set ?data
    ⋀p n. (p,n) ∈ set assumps ⟹ satisfies-evaluation xs p n
    using get-all-valuations[of [] xs]
    by blast
  then have assump-to-atom-eval: (eval (assump-to-atom-fm assumps) xs)
    using assump-to-atom-fm-eval
    by blast
 then have a-in: (assumps, signs) ∈ set (sign-determination-inner ?reindexed-univ-qs
[])
    using assumps-signs(1)
    by auto
 from sign-determination-inner-gives-noncomp-signs-at-roots[OF a-in assumps-signs(2)]
  have signs-is-csvs: set signs =
    consistent-sign-vectors-R (map (eval-mpoly-poly xs) ?reindexed-univ-qs) UNIV
    by auto

  have ⋀ sign. sign ∈ set signs ⟹
        lookup-sem-M F (zip ?qs sign) = (Some True)
  proof −
    fix sign
    assume sign ∈ set signs
   have ∃(x::real). sign = consistent-sign-vec (map (eval-mpoly-poly xs) ?reindexed-univ-qs)
x
      using signs-is-csvs unfolding consistent-sign-vectors-R-def
      using ‹sign ∈ set signs› by auto
   then obtain x where x-prop: sign = consistent-sign-vec (map (eval-mpoly-poly
xs) ?reindexed-univ-qs) x
      by auto
   have map-rel1: map (Sturm-Tarski.sign) (map (λp. poly p x) (map (eval-mpoly-poly
xs) (map (map-poly (lowerPoly 0 1)) (univariate-in (extract-polys F) 0))))
    = (consistent-sign-vec (map (eval-mpoly-poly xs) ?reindexed-univ-qs)) x
```

```
    unfolding consistent-sign-vec-def Sturm-Tarski.sign-def
    by auto
  then have  map-rel2: map (eval-mpoly (x # xs)) (extract-polys F) =
   map (λp. poly p x) (map (eval-mpoly-poly xs) (map (map-poly (lowerPoly 0 1))
(univariate-in (extract-polys F) 0)))
    using reindexed-univ-qs-eval[of - (extract-polys F)] by auto
    then have map-rel3: map Sturm-Tarski.sign (map (eval-mpoly (x # xs))
(extract-polys F)) =
   map (Sturm-Tarski.sign) (map (λp. poly p x) (map (eval-mpoly-poly xs) (map
(map-poly (lowerPoly 0 1)) (univariate-in (extract-polys F) 0))))
    by auto
  have map-rel4: map Sturm-Tarski.sign (map (eval-mpoly (x # xs)) (extract-polys
F)) =  map (mpoly-sign (x#xs)) ?qs
    unfolding mpoly-sign-def by auto
  have map (mpoly-sign (x#xs)) ?qs =(consistent-sign-vec (map (eval-mpoly-poly
xs) ?reindexed-univ-qs)) x
    using map-rel1 map-rel2 map-rel3 map-rel4
    by (metis (no-types, lifting) list.inj-map-strong of-rat-hom.injectivity)

  then have sign = map (mpoly-sign (x#xs)) ?qs
    using x-prop by auto
  then have Some (eval F (x#xs)) = lookup-sem-M F (zip ?qs sign)
    using assms(1) extract-polys-semantics by auto
  then show lookup-sem-M F (zip ?qs sign) = (Some True)
    using assms(2) by auto
 qed
 then have list-all (λ sign.
      let paired-signs = zip ?qs sign in
        lookup-sem-M F paired-signs = (Some True))
      signs
  by (meson Ball-set-list-all)
 then have h2: (assumps, signs) ∈ set ?new-data
  using assumps-signs(1)
  by (smt (verit, del-insts) case-prod-conv mem-Collect-eq set-filter)

 show ?thesis
  using h1 h2 assump-to-atom-eval create-disjunction-true
  by presburger
qed

lemma eval-elim-forall-correct:
 fixes F:: atom fm
 assumes countQuantifiers F = 0
 shows (∀ x. (eval F (x#xs))) = eval (elim-forall F) xs
 using eval-elim-forall-correct2 eval-elim-forall-correct1
 using assms by blast


theorem elim-forall-correct:
```

fixes *F*:: *atom fm*
assumes *countQuantifiers F = 0*
shows *eval* (*AllQ F*) *xs* = *eval* (*elim-forall F*) *xs*
using *eval-elim-forall-correct*
using *assms eval.simps*(*8*) **by** *blast*

lemma *elim-exists-correct*:
fixes *F*:: *atom fm*
assumes *countQuantifiers F = 0*
shows *eval* (*ExQ F*) *xs* = *eval* (*elim-exist F*) *xs*
using *elim-forall-correct*
by (*metis* (*no-types*, *opaque-lifting*) *assms countQuantifiers.simps*(*6*) *elim-exist-def eval.simps*(*6*) *eval.simps*(*7*) *eval.simps*(*8*))

17.12 Correctness of QE

lemma *assump-to-atom-no-quantifiers*:
shows *countQuantifiers* (*assump-to-atom-fm a*) = *0*
proof (*induct a*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a1 a2*)
then show *?case*
using *countQuantifiers.simps*
by (*smt* (*verit*, *best*) *add.right-neutral assump-to-atom-fm.elims list.simps*(*1*))
qed

lemma *create-disjunction-no-quantifiers*:
shows *countQuantifiers* (*create-disjunction ell*) = *0*
proof (*induct ell*)
case *Nil*
then show *?case* **by** *auto*
next
case (*Cons a ell*)
then show *?case*
using *assump-to-atom-no-quantifiers*
by (*metis add.right-neutral countQuantifiers.simps*(*5*) *create-disjunction.elims list.simps*(*1*) *list.simps*(*3*))
qed

lemma *elim-forall-no-quantifiers*:
fixes *F*:: *atom fm*
shows *countQuantifiers* (*elim-forall F*) = *0*
using *create-disjunction-no-quantifiers*
by (*metis elim-forall.simps*)

lemma *elim-exists-no-quantifiers*:
fixes *F*:: *atom fm*

```
  shows countQuantifiers (elim-exist F) = 0
  using elim-forall-no-quantifiers
  using countQuantifiers.simps(6) elim-exist-def by presburger

lemma qe-removes-quantifiers:
  shows countQuantifiers (qe F) = 0
proof (induct F)
  case TrueF
  then show ?case by auto
next
  case FalseF
  then show ?case by auto
next
  case (Atom x)
  then show ?case by auto
next
  case (And F1 F2)
  then show ?case by auto
next
  case (Or F1 F2)
  then show ?case by auto
next
  case (Neg F)
  then show ?case by auto
next
  case (ExQ F)
  then show ?case
    using elim-exists-no-quantifiers qe.simps(7) by presburger
next
  case (AllQ F)
  then show ?case
    using elim-forall-no-quantifiers
    using qe.simps(8) by presburger
next
  case (ExN n F)
  then show ?case
  proof (induct n)
    case 0
    then show ?case
      by auto
  next
    case (Suc n)
    then show ?case
      using elim-exists-no-quantifiers
      by simp
  qed
next
  case (AllN n F)
  then show ?case
```

```
  proof (induct n)
    case 0
    then show ?case
      by auto
  next
    case (Suc n)
    then show ?case
      using elim-forall-no-quantifiers
      by (metis funpow.simps(2) o-apply qe.simps(9))
  qed
qed

lemma elim-exist-N-correct:
  assumes countQuantifiers F = 0
  shows eval (ExN n F) xs = eval ((elim-exist ^^ n) F) xs
  using assms
proof (induct n arbitrary: xs F)
  case 0
  then show ?case
    by auto
next
  case (Suc n)
  have eval (ExN (Suc n) F) xs = eval (ExN n (ExQ F)) xs
    using unwrapExist' by auto
  moreover have ... = eval (ExN n (elim-exist F)) xs
    using elim-exists-correct Suc.prems
    by auto
  moreover have ... = eval ((elim-exist ^^ n) (elim-exist F)) xs
    using Suc.hyps[of elim-exist F] elim-exists-no-quantifiers
    by auto
  moreover have ... = eval ((elim-exist ^^ (n+1)) F) xs
    using funpow-Suc-right unfolding o-def
    by (smt (verit, best) o-apply semiring-norm(174))
  ultimately show ?case
    by (metis semiring-norm(174))
qed

lemma elim-all-N-correct:
  assumes countQuantifiers F = 0
  shows eval (AllN n F) xs = eval ((elim-forall ^^ n) F) xs
  using assms
proof (induct n arbitrary: xs F)
  case 0
  then show ?case
    by (metis clearQuantifiers.simps(11) funpow-0 opt')
next
  case (Suc n)
  have eval (AllN (Suc n) F) xs = eval (AllN n (AllQ F)) xs
    using unwrapForall' by auto
```

```
  moreover have ... =  eval (AllN n (elim-forall F)) xs
    using elim-forall-correct Suc.prems
    using eval.simps(9) by presburger
  moreover have ... =  eval ((elim-forall ^^ n) (elim-forall F)) xs
    using Suc.hyps[of  elim-forall F] elim-forall-no-quantifiers
    by presburger
  moreover have ... =  eval ((elim-forall ^^ (n+1)) F) xs
    using funpow-Suc-right unfolding o-def
    by (smt (verit, best) o-apply semiring-norm(174))
  ultimately show ?case
    by (metis semiring-norm(174))
qed

theorem qe-correct:
  fixes F:: atom fm
  shows eval F xs = eval (qe F) xs
proof (induct F arbitrary: xs)
  case TrueF
  then show ?case by auto
next
  case FalseF
  then show ?case by auto
next
  case (Atom x)
  then show ?case by auto
next
  case (And F1 F2)
  then show ?case
    using eval.simps
    by auto
next
  case (Or F1 F2)
  then show ?case
    using eval.simps
    by auto
next
  case (Neg F)
  then show ?case
    using eval.simps
    by auto
next
  case (ExQ F)
  have countQuantifiers (qe F) = 0
    using qe-removes-quantifiers by auto
  from elim-exists-correct[OF this]
  have h: eval (ExQ (qe F)) xs = eval (elim-exist (qe F)) xs
    .
  have eval (ExQ F) xs = eval ( ExQ (qe F)) xs
    using ExQ.hyps
```

```
    by simp
  then show ?case
    using h
    by auto
next
  case (AllQ F)
  have countQuantifiers (qe F) = 0
    using qe-removes-quantifiers by auto
  from elim-forall-correct[OF this]
  have h: eval (AllQ (qe F)) xs = eval (elim-forall (qe F)) xs
    .
  have eval (AllQ F) xs = eval (AllQ (qe F)) xs
    using AllQ.hyps
    by simp
  then show ?case
    using h
    using qe.simps(8) by presburger
next
  case (ExN n F)
  have cq: countQuantifiers (qe F) = 0
    using qe-removes-quantifiers by auto
  have h: eval (ExN n F) xs = eval (ExN n (qe F)) xs
    using ExN.hyps
    by simp
  have eval (ExN n (qe F)) xs = eval ((elim-exist ^^ n) (qe F)) xs
    using elim-exist-N-correct[OF cq] .
  then show ?case
    using h by auto
next
  case (AllN n F)
  have cq: countQuantifiers (qe F) = 0
    using qe-removes-quantifiers by auto
  have h: eval (AllN n F) xs = eval (AllN n (qe F)) xs
    using AllN.hyps
    by simp
  have eval (AllN n (qe F)) xs = eval ((elim-forall ^^ n) (qe F)) xs
    using elim-all-N-correct[OF cq] .
  then show ?case
    using h by auto
qed

theorem qe-extended-correct:
  fixes F:: atom fm
  shows eval F xs = eval (qe-with-VS F) xs
  using qe-correct VSLEG
  by (simp add: qe-with-VS-def)

end
```

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