

Subresultants*

Sebastian Joosten, René Thiemann and Akihisa Yamada

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Abstract

We formalize the theory of subresultants and the subresultant polynomial remainder sequence as described by Brown and Traub. As a result, we obtain efficient certified algorithms for computing the resultant and the greatest common divisor of polynomials.

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1 Introduction

Computing the gcd of two polynomials can be done via the Euclidean algorithm, if the domain of the polynomials is a field. For non-field polynomials, one has to replace the modulo operation by the pseudo-modulo operation, which results in the exponential growth of coefficients in the gcd algorithm. To counter this problem, one may divide the intermediate polynomials by their contents in every iteration of the gcd algorithm. This is precisely the way how currently resultants and gcds are computed in Isabelle.

Computing contents in every iteration is a costly operation, and therefore Brown and Traub have developed the subresultant PRS (polynomial remainder sequence) algorithm [1, 2]. It avoids intermediate content computation and at the same time keeps the coefficients small, i.e., the coefficients grow at most polynomially.

The soundness of the subresultant PRS gcd algorithm is in principle similar to the Euclidean algorithm, i.e., the intermediate polynomials that are computed in both algorithms differ only by a constant factor. The major problem is to prove that all the performed divisions are indeed exact divisions. To this end, we formalize the fundamental theorem of Brown and Traub as well as the resulting algorithms by following the original (condensed) proofs. This is in contrast to a similar Coq formalization by Mahboubi [4], which follows another proof based on polynomial determinants.

As a consequence of the new algorithms, we significantly increased the speed of the algebraic number implementation [5] which heavily relies upon the computation of resultants of bivariate polynomials.

2 Resultants

This theory defines the Sylvester matrix and the resultant and contains basic facts about these notions. After the connection between resultants and subresultants has been established, we then use properties of subresultants to transfer them to resultants. Remark: these properties have previously been proven separately for both resultants and subresultants; and this is the reason for splitting the theory of resultants in two parts, namely “Resultant-Prelim” and “Resultant” which is located in the Algebraic-Number AFP-entry.

theory *Resultant-Prelim*

imports

Jordan-Normal-Form.Determinant

Polynomial-Interpolation.Ring-Hom-Poly

begin

Sylvester matrix

definition *sylvester-mat-sub* :: *nat* \Rightarrow *nat* \Rightarrow 'a *poly* \Rightarrow 'a *poly* \Rightarrow 'a :: *zero mat*
where

sylvester-mat-sub $m\ n\ p\ q \equiv$
 $\text{mat } (m+n)\ (m+n)\ (\lambda\ (i,j)).$
 if $i < n$ then
 if $i \leq j \wedge j - i \leq m$ then $\text{coeff } p\ (m + i - j)$ else 0
 else if $i - n \leq j \wedge j \leq i$ then $\text{coeff } q\ (i-j)$ else 0

definition *sylvester-mat* :: 'a poly \Rightarrow 'a poly \Rightarrow 'a :: zero mat **where**
sylvester-mat $p\ q \equiv \text{sylvester-mat-sub } (\text{degree } p)\ (\text{degree } q)\ p\ q$

lemma *sylvester-mat-sub-dim[simp]*:
 fixes $m\ n\ p\ q$
 defines $S \equiv \text{sylvester-mat-sub } m\ n\ p\ q$
 shows $\text{dim-row } S = m+n$ and $\text{dim-col } S = m+n$
 <proof>

lemma *sylvester-mat-sub-carrier*:
 shows $\text{sylvester-mat-sub } m\ n\ p\ q \in \text{carrier-mat } (m+n)\ (m+n)$ <proof>

lemma *sylvester-mat-dim[simp]*:
 fixes $p\ q$
 defines $d \equiv \text{degree } p + \text{degree } q$
 shows $\text{dim-row } (\text{sylvester-mat } p\ q) = d$ $\text{dim-col } (\text{sylvester-mat } p\ q) = d$
 <proof>

lemma *sylvester-carrier-mat*:
 fixes $p\ q$
 defines $d \equiv \text{degree } p + \text{degree } q$
 shows $\text{sylvester-mat } p\ q \in \text{carrier-mat } d\ d$ <proof>

lemma *sylvester-mat-sub-index*:
 fixes $p\ q$
 assumes $i: i < m+n$ and $j: j < m+n$
 shows $\text{sylvester-mat-sub } m\ n\ p\ q\ \$\$ (i,j) =$
 (if $i < n$ then
 if $i \leq j \wedge j - i \leq m$ then $\text{coeff } p\ (m + i - j)$ else 0
 else if $i - n \leq j \wedge j \leq i$ then $\text{coeff } q\ (i-j)$ else 0)
 <proof>

lemma *sylvester-index-mat*:
 fixes $p\ q$
 defines $m \equiv \text{degree } p$ and $n \equiv \text{degree } q$
 assumes $i: i < m+n$ and $j: j < m+n$
 shows $\text{sylvester-mat } p\ q\ \$\$ (i,j) =$
 (if $i < n$ then
 if $i \leq j \wedge j - i \leq m$ then $\text{coeff } p\ (m + i - j)$ else 0
 else if $i - n \leq j \wedge j \leq i$ then $\text{coeff } q\ (i - j)$ else 0)
 <proof>

lemma *sylvester-index-mat2*:

fixes $p\ q :: 'a :: \text{comm-semiring-1 poly}$
defines $m \equiv \text{degree } p$ **and** $n \equiv \text{degree } q$
assumes $i: i < m+n$ **and** $j: j < m+n$
shows $\text{sylvester-mat } p\ q\ \$\$ (i,j) =$
 (if $i < n$ *then* $\text{coeff } (\text{monom } 1\ (n - i) * p)\ (m+n-j)$
 else $\text{coeff } (\text{monom } 1\ (m + n - i) * q)\ (m+n-j)$)
 <proof>

lemma $\text{sylvester-mat-sub-0[simp]}$: $\text{sylvester-mat-sub } 0\ n\ 0\ q = 0_m\ n\ n$
 <proof>

lemma $\text{sylvester-mat-0[simp]}$: $\text{sylvester-mat } 0\ q = 0_m\ (\text{degree } q)\ (\text{degree } q)$
 <proof>

lemma $\text{sylvester-mat-const[simp]}$:
fixes $a :: 'a :: \text{semiring-1}$
shows $\text{sylvester-mat } [:a:]\ q = a \cdot_m\ 1_m\ (\text{degree } q)$
 and $\text{sylvester-mat } p\ [:a:] = a \cdot_m\ 1_m\ (\text{degree } p)$
 <proof>

lemma $\text{sylvester-mat-sub-map}$:
assumes $f0: f\ 0 = 0$
shows $\text{map-mat } f\ (\text{sylvester-mat-sub } m\ n\ p\ q) = \text{sylvester-mat-sub } m\ n\ (\text{map-poly } f\ p)$
 (is ?l = ?r)
 <proof>

definition $\text{resultant} :: 'a\ \text{poly} \Rightarrow 'a\ \text{poly} \Rightarrow 'a :: \text{comm-ring-1}$ **where**
 $\text{resultant } p\ q = \text{det } (\text{sylvester-mat } p\ q)$

Resultant, but the size of the base Sylvester matrix is given.

definition $\text{resultant-sub } m\ n\ p\ q = \text{det } (\text{sylvester-mat-sub } m\ n\ p\ q)$

lemma resultant-sub : $\text{resultant } p\ q = \text{resultant-sub } (\text{degree } p)\ (\text{degree } q)\ p\ q$
 <proof>

lemma $\text{resultant-const[simp]}$:
fixes $a :: 'a :: \text{comm-ring-1}$
shows $\text{resultant } [:a:]\ q = a \wedge (\text{degree } q)$
 and $\text{resultant } p\ [:a:] = a \wedge (\text{degree } p)$
 <proof>

lemma resultant-1[simp] :
fixes $p :: 'a :: \text{comm-ring-1 poly}$
shows $\text{resultant } 1\ p = 1$ $\text{resultant } p\ 1 = 1$
 <proof>

lemma resultant-0[simp] :

fixes $p :: 'a :: \text{comm-ring-1 poly}$
assumes $\text{degree } p > 0$
shows $\text{resultant } 0 p = 0 \text{ resultant } p 0 = 0$
 $\langle \text{proof} \rangle$

lemma (**in** comm-ring-hom) $\text{resultant-map-poly}$: $\text{degree } (\text{map-poly hom } p) = \text{degree } p \implies$
 $\text{degree } (\text{map-poly hom } q) = \text{degree } q \implies \text{resultant } (\text{map-poly hom } p) (\text{map-poly hom } q) = \text{hom } (\text{resultant } p q)$
 $\langle \text{proof} \rangle$

lemma (**in** inj-comm-ring-hom) resultant-hom : $\text{resultant } (\text{map-poly hom } p) (\text{map-poly hom } q) = \text{hom } (\text{resultant } p q)$
 $\langle \text{proof} \rangle$

end

3 Dichotomous Lazard

This theory contains Lazard's optimization in the computation of the sub-resultant PRS as described by Ducos [3, Section 2].

theory $\text{Dichotomous-Lazard}$
imports
 $\text{HOL-Computational-Algebra.Polynomial-Factorial}$
begin

lemma $\text{power-fract}[simp]$: $(\text{Fract } a b)^{\wedge} n = \text{Fract } (a^{\wedge} n) (b^{\wedge} n)$
 $\langle \text{proof} \rangle$

lemma $\text{range-to-fract-dvd-iff}$: **assumes** $b: b \neq 0$
shows $\text{Fract } a b \in \text{range to-fract} \iff b \text{ dvd } a$
 $\langle \text{proof} \rangle$

lemma $\text{Fract-cases-coprime}$ [cases type: fract]:
fixes $q :: 'a :: \text{factorial-ring-gcd fract}$
obtains $(\text{Fract}) a b$ **where** $q = \text{Fract } a b \ b \neq 0 \ \text{coprime } a b$
 $\langle \text{proof} \rangle$

lemma to-fract-power-le : **fixes** $a :: 'a :: \text{factorial-ring-gcd fract}$
assumes $\text{no-fract}: a * b^{\wedge} e \in \text{range to-fract}$
and $a: a \in \text{range to-fract}$
and $le: f \leq e$
shows $a * b^{\wedge} f \in \text{range to-fract}$
 $\langle \text{proof} \rangle$

lemma $\text{div-divide-to-fract}$: **assumes** $x \in \text{range to-fract}$
and $x = (y :: 'a :: \text{idom-divide fract}) / z$
and $x' = y' \text{ div } z'$

```

and  $y = \text{to-fract } y' \ z = \text{to-fract } z'$ 
shows  $x = \text{to-fract } x'$ 
⟨proof⟩

```

```

declare divmod-nat-def[termination-simp]

```

```

fun dichotomous-Lazard :: 'a :: idom-divide  $\Rightarrow$  'a  $\Rightarrow$  nat  $\Rightarrow$  'a where
  dichotomous-Lazard x y n = (if n  $\leq$  1 then if n = 1 then x else 1 else
    let (d,r) = Divides.divmod-nat n 2;
        rec = dichotomous-Lazard x y d;
        recsq = rec * rec div y in
    if r = 0 then recsq else recsq * x div y)

```

```

lemma dichotomous-Lazard-main: fixes x :: 'a :: idom-divide
assumes  $\bigwedge i. i \leq n \implies (\text{to-fract } x)^i / (\text{to-fract } y)^{i-1} \in \text{range } \text{to-fract}$ 
shows  $\text{to-fract } (\text{dichotomous-Lazard } x y n) = (\text{to-fract } x)^n / (\text{to-fract } y)^{n-1}$ 
⟨proof⟩

```

```

lemma dichotomous-Lazard: fixes x :: 'a :: factorial-ring-gcd
assumes  $(\text{to-fract } x)^n / (\text{to-fract } y)^{n-1} \in \text{range } \text{to-fract}$ 
shows  $\text{to-fract } (\text{dichotomous-Lazard } x y n) = (\text{to-fract } x)^n / (\text{to-fract } y)^{n-1}$ 
⟨proof⟩

```

```

declare dichotomous-Lazard.simps[simp del]

```

```

end

```

4 Binary Exponentiation

This theory defines the standard algorithm for binary exponentiation, or exponentiation by squaring.

```

theory Binary-Exponentiation

```

```

imports

```

```

  Main

```

```

begin

```

```

declare divmod-nat-def[termination-simp]

```

```

context monoid-mult

```

```

begin

```

```

fun binary-power :: 'a  $\Rightarrow$  nat  $\Rightarrow$  'a where
  binary-power x n = (if n = 0 then 1 else
    let (d,r) = Divides.divmod-nat n 2;
        rec = binary-power (x * x) d in
    if r = 0 then rec else rec * x)

```

lemma *binary-power*[simp]: *binary-power* = (^)
⟨proof⟩

lemma *binary-power-code-unfold*[code-unfold]: (^) = *binary-power*
⟨proof⟩

declare *binary-power.simps*[simp del]
end
end

5 Homomorphisms

We register two homomorphism, namely lifting constants to polynomials, and lifting elements of some domain into their fraction field.

theory *More-Homomorphisms*
imports *Polynomial-Interpolation.Ring-Hom-Poly*
Jordan-Normal-Form.Determinant
begin

abbreviation (*input*) *coeff-lift* == $\lambda a. [: a :]$

interpretation *coeff-lift-hom: inj-comm-monoid-add-hom coeff-lift* ⟨proof⟩

interpretation *coeff-lift-hom: inj-ab-group-add-hom coeff-lift* ⟨proof⟩

interpretation *coeff-lift-hom: inj-comm-semiring-hom coeff-lift*
⟨proof⟩

interpretation *coeff-lift-hom: inj-comm-ring-hom coeff-lift* ⟨proof⟩

interpretation *coeff-lift-hom: inj-idom-hom coeff-lift* ⟨proof⟩

The following rule is incompatible with existing simp rules.

declare *coeff-lift-hom.hom-mult*[simp del]
declare *coeff-lift-hom.hom-add*[simp del]
declare *coeff-lift-hom.hom-uminus*[simp del]

interpretation *to-fract-hom: inj-comm-ring-hom to-fract* ⟨proof⟩

interpretation *to-fract-hom: idom-hom to-fract* ⟨proof⟩

interpretation *to-fract-hom: inj-idom-hom to-fract* ⟨proof⟩

end

6 Polynomial coefficients with integer index

We provide a function to access the coefficients of a polynomial via an integer index. Then index-shifting becomes more convenient, e.g., compare in the lemmas for accessing the coefficient of a product with a monomial there is no special case for integer coefficients, whereas for natural number coefficients there is a case-distinction.

theory *Coeff-Int*

imports

Polynomial-Interpolation.Missing-Polynomial

Jordan-Normal-Form.Missing-Permutations

begin

definition *coeff-int* :: 'a :: zero poly \Rightarrow int \Rightarrow 'a **where**
coeff-int p i = (if i < 0 then 0 else coeff p (nat i))

lemma *coeff-int-eq-0*: i < 0 \vee i > int (degree p) \implies *coeff-int* p i = 0
<proof>

lemma *coeff-int-smult[simp]*: *coeff-int* (smult c p) i = c * *coeff-int* p i
<proof>

lemma *coeff-int-signof-mult*: *coeff-int* (signof x * f) i = signof x * (*coeff-int* f i)
<proof>

lemma *coeff-int-sum*: *coeff-int* (sum p A) i = ($\sum x \in A.$ *coeff-int* (p x) i)
<proof>

lemma *coeff-int-0[simp]*: *coeff-int* f 0 = coeff f 0 <proof>

lemma *coeff-int-monom-mult*: *coeff-int* (monom a d * f) i = (a * *coeff-int* f (i - d))
<proof>

lemma *coeff-prod-const*: **assumes** finite xs **and** y \notin xs
and $\bigwedge x. x \in xs \implies$ degree (f x) = 0
shows *coeff* (prod f (insert y xs)) i = prod ($\lambda x. \text{coeff } (f x) 0$) xs * *coeff* (f y) i
<proof>

lemma *coeff-int-prod-const*: **assumes** finite xs **and** y \notin xs
and $\bigwedge x. x \in xs \implies$ degree (f x) = 0
shows *coeff-int* (prod f (insert y xs)) i = prod ($\lambda x. \text{coeff-int } (f x) 0$) xs * *coeff-int* (f y) i
<proof>

lemma *coeff-int[simp]*: *coeff-int* p n = coeff p n <proof>

lemma *coeff-int-minus[simp]*:
coeff-int (a - b) i = *coeff-int* a i - *coeff-int* b i
<proof>

lemma *coeff-int-pCons-0[simp]*: *coeff-int* (pCons 0 b) i = *coeff-int* b (i - 1)
<proof>

end

7 Subresultants and the subresultant PRS

This theory contains most of the soundness proofs of the subresultant PRS algorithm, where we closely follow the papers of Brown [1] and Brown and Traub [2]. This is in contrast to a similar Coq formalization of Mahboubi [4] which is based on polynomial determinants.

Whereas the current file only contains an algorithm to compute the resultant of two polynomials efficiently, there is another theory “Subresultant-Gcd” which also contains the algorithm to compute the GCD of two polynomials via the subresultant algorithm. In both algorithms we integrate Lazard’s optimization in the dichotomous version, but not the second optimization described by Ducos [3].

```

theory Subresultant
imports
  Resultant-Prelim
  Dichotomous-Lazard
  Binary-Exponentiation
  More-Homomorphisms
  Coeff-Int
begin

```

7.1 Algorithm

```

context
  fixes div-exp :: 'a :: idom-divide  $\Rightarrow$  'a  $\Rightarrow$  nat  $\Rightarrow$  'a
begin
partial-function(tailrec) subresultant-prs-main where
  subresultant-prs-main f g c = (let
    m = degree f;
    n = degree g;
    lf = lead-coeff f;
    lg = lead-coeff g;
     $\delta$  = m - n;
    d = div-exp lg c  $\delta$ ;
    h = pseudo-mod f g
  in if h = 0 then (g,d)
    else subresultant-prs-main g (sdiv-poly h ((-1) ^ ( $\delta$  + 1) * lf * (c ^  $\delta$ ))) d)

```

```

definition subresultant-prs where
  [code del]: subresultant-prs f g = (let
    h = pseudo-mod f g;
     $\delta$  = (degree f - degree g);
    d = lead-coeff g ^  $\delta$ 
  in if h = 0 then (g,d)
    else subresultant-prs-main g ((- 1) ^ ( $\delta$  + 1) * h) d)

```

```

definition resultant-impl-main where
  [code del]: resultant-impl-main G1 G2 = (if G2 = 0 then (if degree G1 = 0 then

```

1 else 0) else
 case subresultant-prs G1 G2 of
 (Gk,hk) ⇒ (if degree Gk = 0 then hk else 0))

definition *resultant-impl-generic* **where**
resultant-impl-generic f g =
 (if length (coeffs f) ≥ length (coeffs g) then resultant-impl-main f g
 else let res = resultant-impl-main g f in
 if even (degree f) ∨ even (degree g) then res else - res)
end

definition *basic-div-exp* :: 'a :: idom-divide ⇒ 'a ⇒ nat ⇒ 'a **where**
basic-div-exp x y n = xⁿ div y⁽ⁿ⁻¹⁾

Using *basic-div-exp* we obtain a more generic implementation, which is however less efficient. It is currently not further developed, except for getting the raw soundness statement.

definition *resultant-impl-idom-divide* :: 'a poly ⇒ 'a poly ⇒ 'a :: idom-divide **where**
resultant-impl-idom-divide = resultant-impl-generic *basic-div-exp*

The default variant uses the optimized computation *dichotomous-Lazard*. For this variant, later on optimized code-equations are proven. However, the implementation restricts to sort *factorial-ring-gcd*.

definition *resultant-impl* :: 'a poly ⇒ 'a poly ⇒ 'a :: factorial-ring-gcd **where**
 [code del]: *resultant-impl* = resultant-impl-generic *dichotomous-Lazard*

7.2 Soundness Proof for *resultant-impl* = *resultant*

lemma *basic-div-exp*: **assumes** (to-fract x)ⁿ / (to-fract y)⁽ⁿ⁻¹⁾ ∈ range to-fract
shows to-fract (basic-div-exp x y n) = (to-fract x)ⁿ / (to-fract y)⁽ⁿ⁻¹⁾
 ⟨proof⟩

abbreviation *pdivmod* :: 'a::field poly ⇒ 'a poly ⇒ 'a poly × 'a poly
where
pdivmod p q ≡ (p div q, p mod q)

lemma *even-sum-list*: **assumes** $\bigwedge x. x \in \text{set } xs \implies \text{even } (f x) = \text{even } (g x)$
shows even (sum-list (map f xs)) = even (sum-list (map g xs))
 ⟨proof⟩

lemma *for-all-Suc*: $P i \implies (\forall j \geq \text{Suc } i. P j) = (\forall j \geq i. P j)$ **for** P
 ⟨proof⟩

lemma *pseudo-mod-left-0[simp]*: pseudo-mod 0 x = 0
 ⟨proof⟩

lemma *pseudo-mod-right-0[simp]*: pseudo-mod x 0 = x

<proof>

lemma *snd-pseudo-divmod-main-cong*:

assumes $a1 = b1$ $a3 = b3$ $a4 = b4$ $a5 = b5$ $a6 = b6$

shows snd (*pseudo-divmod-main* $a1$ $a2$ $a3$ $a4$ $a5$ $a6$) = snd (*pseudo-divmod-main* $b1$ $b2$ $b3$ $b4$ $b5$ $b6$)

<proof>

lemma *snd-pseudo-mod-smult-invar-right*:

shows (snd (*pseudo-divmod-main* ($x * lc$) q r (*smult* x d) dr n))
= snd (*pseudo-divmod-main* lc q' (*smult* (x^n) r) d dr n)

<proof>

lemma *snd-pseudo-mod-smult-invar-left*:

shows snd (*pseudo-divmod-main* lc q (*smult* x r) d dr n)
= *smult* x (snd (*pseudo-divmod-main* lc q' r d dr n))

<proof>

lemma *snd-pseudo-mod-smult-left[simp]*:

shows snd (*pseudo-divmod* (*smult* ($x::'a::idom$) p) q) = (*smult* x (snd (*pseudo-divmod* p q)))

<proof>

lemma *pseudo-mod-smult-right*:

assumes ($x::'a::idom$) $\neq 0$ $q\neq 0$

shows (*pseudo-mod* p (*smult* ($x::'a::idom$) q)) = (*smult* ($x^{(Suc$ (*length* (*coeffs* p)) - *length* (*coeffs* q))) (*pseudo-mod* p q))

<proof>

lemma *pseudo-mod-zero[simp]*:

pseudo-mod 0 f = ($0::'a::\{idom\}$ *poly*)

pseudo-mod f 0 = f

<proof>

lemma *prod-combine*:

assumes $j \leq i$

shows f $i * (\prod_{l \leftarrow [j..<i]}$. (f $l :: 'a::comm-monoid-mult$)) = *prod-list* (*map* f $[j..<Suc$ $i]$)

<proof>

lemma *prod-list-minus-1-exp*: *prod-list* (*map* (λ i . $(-1)^{(f$ $i)$) xs)

= $(-1)^{(\text{sum-list } (\text{map } f \text{ } xs))}$

<proof>

lemma *minus-1-power-even*: $(- (1 :: 'b :: comm-ring-1))^{k}$ = (*if even* k *then* 1 *else* (-1))

<proof>

lemma *minus-1-even-eqI*: **assumes** *even k = even l* **shows**

$$(- (1 :: 'b :: \text{comm-ring-1}))^k = (- 1)^l$$

<proof>

lemma (**in** *comm-monoid-mult*) *prod-list-multf*:

$$\left(\prod_{x \leftarrow xs} f x * g x\right) = \text{prod-list } (\text{map } f xs) * \text{prod-list } (\text{map } g xs)$$

<proof>

lemma *inverse-prod-list*: *inverse (prod-list xs) = prod-list (map inverse (xs :: 'a :: field list))*

<proof>

definition *pow-int* :: 'a :: field \Rightarrow int \Rightarrow 'a **where**

$$\text{pow-int } x e = (\text{if } e < 0 \text{ then } 1 / (x ^ (\text{nat } (-e))) \text{ else } x ^ (\text{nat } e))$$

lemma *pow-int-0[simp]*: *pow-int x 0 = 1* *<proof>*

lemma *pow-int-1[simp]*: *pow-int x 1 = x* *<proof>*

lemma *exp-pow-int*: *x ^ n = pow-int x n*

<proof>

lemma *pow-int-add*: **assumes** *x: x \neq 0* **shows** *pow-int x (a + b) = pow-int x a * pow-int x b*

<proof>

lemma *pow-int-mult*: *pow-int (x * y) a = pow-int x a * pow-int y a*

<proof>

lemma *pow-int-base-1[simp]*: *pow-int 1 a = 1*

<proof>

lemma *pow-int-divide*: *a / pow-int x b = a * pow-int x (-b)*

<proof>

lemma *divide-prod-assoc*: *x / (y * z :: 'a :: field) = x / y / z* *<proof>*

lemma *minus-1-inverse-pow[simp]*: *x / (-1)^n = (x :: 'a :: field) * (-1)^n*

<proof>

definition *subresultant-mat* :: nat \Rightarrow 'a :: comm-ring-1 poly \Rightarrow 'a poly \Rightarrow 'a poly mat **where**

$$\begin{aligned} & \text{subresultant-mat } J F G = (\text{let} \\ & \quad dg = \text{degree } G; df = \text{degree } F; f = \text{coeff-int } F; g = \text{coeff-int } G; n = (df - J) \\ & \quad + (dg - J) \\ & \quad \text{in mat } n n (\lambda (i,j). \text{if } j < dg - J \text{ then} \end{aligned}$$

$\text{if } i = n - 1 \text{ then monom } 1 \text{ (} dg - J - 1 - j \text{) * } F \text{ else [: } f \text{ (} df - \text{int } i + \text{int } j \text{) :]}$
 $\text{else let } jj = j - (dg - J) \text{ in}$
 $\text{if } i = n - 1 \text{ then monom } 1 \text{ (} df - J - 1 - jj \text{) * } G \text{ else [: } g \text{ (} dg - \text{int } i + \text{int } jj \text{) :])]$

lemma *subresultant-mat-dim*[simp]:

fixes $j \ p \ q$
defines $S \equiv \text{subresultant-mat } j \ p \ q$
shows $\text{dim-row } S = (\text{degree } p - j) + (\text{degree } q - j)$ **and** $\text{dim-col } S = (\text{degree } p - j) + (\text{degree } q - j)$
 $\langle \text{proof} \rangle$

definition *subresultant'-mat* :: $\text{nat} \Rightarrow \text{nat} \Rightarrow 'a :: \text{comm-ring-1 poly} \Rightarrow 'a \text{ poly} \Rightarrow 'a \text{ mat}$ **where**

$\text{subresultant}'\text{-mat } J \ l \ F \ G = (\text{let}$
 $\gamma = \text{degree } G; \varphi = \text{degree } F; f = \text{coeff-int } F; g = \text{coeff-int } G; n = (\varphi - J) + (\gamma - J)$
 $\text{in mat } n \ n \ (\lambda \ (i,j). \text{if } j < \gamma - J \text{ then}$
 $\text{if } i = n - 1 \text{ then } (f \ (l - \text{int } (\gamma - J - 1) + \text{int } j)) \text{ else } (f \ (\varphi - \text{int } i + \text{int } j))$
 $\text{else let } jj = j - (\gamma - J) \text{ in}$
 $\text{if } i = n - 1 \text{ then } (g \ (l - \text{int } (\varphi - J - 1) + \text{int } jj)) \text{ else } (g \ (\gamma - \text{int } i + \text{int } jj))))$

lemma *subresultant-index-mat*:

fixes $F \ G$
assumes $i: i < (\text{degree } F - J) + (\text{degree } G - J)$ **and** $j: j < (\text{degree } F - J) + (\text{degree } G - J)$
shows $\text{subresultant-mat } J \ F \ G \ \S\S \ (i,j) =$
 $(\text{if } j < \text{degree } G - J \text{ then}$
 $\text{if } i = (\text{degree } F - J) + (\text{degree } G - J) - 1 \text{ then monom } 1 \text{ (} \text{degree } G - J - 1 - j \text{) * } F \text{ else ([: } \text{coeff-int } F \text{ (} \text{degree } F - \text{int } i + \text{int } j \text{) :])}$
 $\text{else let } jj = j - (\text{degree } G - J) \text{ in}$
 $\text{if } i = (\text{degree } F - J) + (\text{degree } G - J) - 1 \text{ then monom } 1 \text{ (} \text{degree } F - J - 1 - jj \text{) * } G \text{ else ([: } \text{coeff-int } G \text{ (} \text{degree } G - \text{int } i + \text{int } jj \text{) :])}$
 $\langle \text{proof} \rangle$

definition *subresultant* :: $\text{nat} \Rightarrow 'a :: \text{comm-ring-1 poly} \Rightarrow 'a \text{ poly} \Rightarrow 'a \text{ poly}$ **where**
 $\text{subresultant } J \ F \ G = \text{det } (\text{subresultant-mat } J \ F \ G)$

lemma *subresultant-smult-left*: **assumes** $(c :: 'a :: \{\text{comm-ring-1, semiring-no-zero-divisors}\}) \neq 0$

shows $\text{subresultant } J \ (\text{smult } c \ f) \ g = \text{smult } (c \ ^{(\text{degree } g - J)}) \ (\text{subresultant } J \ f \ g)$
 $\langle \text{proof} \rangle$

lemma *subresultant-swap*:

shows $\text{subresultant } J f g = \text{smult } ((- 1) \wedge ((\text{degree } f - J) * (\text{degree } g - J)))$
(subresultant J f g)
 ⟨proof⟩

lemma *subresultant-smult-right*: **assumes** $(c :: 'a :: \{\text{comm-ring-1, semiring-no-zero-divisors}\}) \neq 0$
shows $\text{subresultant } J f (\text{smult } c g) = \text{smult } (c \wedge (\text{degree } f - J)) (\text{subresultant } J f g)$
 ⟨proof⟩

lemma *coeff-subresultant*: $\text{coeff } (\text{subresultant } J F G) l =$
(if degree F - J + (degree G - J) = 0 \wedge l \neq 0 then 0 else det (subresultant'-mat J l F G))
 ⟨proof⟩

lemma *subresultant'-zero-ge*: **assumes** $(\text{degree } f - J) + (\text{degree } g - J) \neq 0$ **and**
 $k \geq \text{degree } f + (\text{degree } g - J)$
shows $\text{det } (\text{subresultant}'\text{-mat } J k f g) = 0$
 ⟨proof⟩

lemma *subresultant'-zero-lt*: **assumes**
 $J: J \leq \text{degree } f \wedge J \leq \text{degree } g \wedge J < k$
and $k: k < \text{degree } f + (\text{degree } g - J)$
shows $\text{det } (\text{subresultant}'\text{-mat } J k f g) = 0$
 ⟨proof⟩

lemma *subresultant'-mat-sylvester-mat*: $\text{transpose-mat } (\text{subresultant}'\text{-mat } 0 0 f g)$
 $= \text{sylvester-mat } f g$
 ⟨proof⟩

lemma *coeff-subresultant-0-0-resultant*: $\text{coeff } (\text{subresultant } 0 f g) 0 = \text{resultant } f g$
 ⟨proof⟩

lemma *subresultant-zero-ge*: **assumes** $k \geq \text{degree } f + (\text{degree } g - J)$
and $(\text{degree } f - J) + (\text{degree } g - J) \neq 0$
shows $\text{coeff } (\text{subresultant } J f g) k = 0$
 ⟨proof⟩

lemma *subresultant-zero-lt*: **assumes** $k < \text{degree } f + (\text{degree } g - J)$
and $J \leq \text{degree } f \wedge J \leq \text{degree } g \wedge J < k$
shows $\text{coeff } (\text{subresultant } J f g) k = 0$
 ⟨proof⟩

lemma *subresultant-resultant*: $\text{subresultant } 0 f g = [; \text{resultant } f g ;]$
 ⟨proof⟩

lemma (**in** *inj-comm-ring-hom*) *subresultant-hom*:
 $\text{map-poly hom } (\text{subresultant } J f g) = \text{subresultant } J (\text{map-poly hom } f) (\text{map-poly hom } g)$

<proof>

We now derive properties of the resultant via the connection to subresultants.

lemma resultant-smult-left: **assumes** $(c :: 'a :: idom) \neq 0$
shows $\text{resultant} (\text{smult } c \ f) \ g = c \wedge \text{degree } g * \text{resultant } f \ g$
<proof>

lemma resultant-smult-right: **assumes** $(c :: 'a :: idom) \neq 0$
shows $\text{resultant } f (\text{smult } c \ g) = c \wedge \text{degree } f * \text{resultant } f \ g$
<proof>

lemma resultant-swap: $\text{resultant } f \ g = (-1)^{\wedge(\text{degree } f * \text{degree } g)} * (\text{resultant } g \ f)$
<proof>

The following equations are taken from Brown-Traub “On Euclid’s Algorithm and the Theory of Subresultant” (BT)

lemma fixes $F \ B \ G \ H :: 'a :: idom \ \text{poly}$ **and** $J :: nat$
defines $df: df \equiv \text{degree } F$
and $dg: dg \equiv \text{degree } G$
and $dh: dh \equiv \text{degree } H$
and $db: db \equiv \text{degree } B$
defines
 $n: n \equiv (df - J) + (dg - J)$
and $f: f \equiv \text{coeff-int } F$
and $b: b \equiv \text{coeff-int } B$
and $g: g \equiv \text{coeff-int } G$
and $h: h \equiv \text{coeff-int } H$
assumes $FGH: F + B * G = H$
and $dfg: df \geq dg$
and $\text{choice}: dg > dh \vee H = 0 \wedge F \neq 0 \wedge G \neq 0$
shows $BT\text{-eq-18}: \text{subresultant } J \ F \ G = \text{smult } ((-1)^{\wedge((df - J) * (dg - J))}) (\text{det} (\text{mat } n \ n) (\lambda \ (i,j).$
 $\quad \text{if } j < df - J$
 $\quad \text{then if } i = n - 1 \text{ then monom } 1 \ ((df - J) - 1 - j) * G$
 $\quad \quad \text{else } [:g \ (\text{int } dg - \text{int } i + \text{int } j):]$
 $\quad \text{else if } i = n - 1 \text{ then monom } 1 \ ((dg - J) - 1 - (j - (df - J))) * H$
 $\quad \quad \text{else } [:h \ (\text{int } df - \text{int } i + \text{int } (j - (df - J))):])$
 $\quad (\text{is } - = \text{smult } ?m1 \ ?right)$
and $BT\text{-eq-19}: dh \leq J \implies J < dg \implies \text{subresultant } J \ F \ G = \text{smult } ($
 $\quad (-1)^{\wedge((df - J) * (dg - J))} * \text{lead-coeff } G \wedge (df - J) * \text{coeff } H \ J \wedge (dg - J$
 $\quad - 1)) \ H$
 $\quad (\text{is } - \implies - \implies - = \text{smult } (- * ?G * ?H) \ H)$
and $BT\text{-lemma-1-12}: J < dh \implies \text{subresultant } J \ F \ G = \text{smult } ($
 $\quad (-1)^{\wedge((df - J) * (dg - J))} * \text{lead-coeff } G \wedge (df - dh)) (\text{subresultant } J \ G \ H)$
and $BT\text{-lemma-1-13}': J = dh \implies dg > dh \vee H \neq 0 \implies \text{subresultant } dh \ F \ G$
 $= \text{smult } ($

$(-1)^{\wedge}((df - dh) * (dg - dh)) * \text{lead-coeff } G^{\wedge} (df - dh) * \text{lead-coeff } H^{\wedge} (dg - dh - 1)) H$
and *BT-lemma-1-14*: $dh < J \implies J < dg - 1 \implies \text{subresultant } J F G = 0$
and *BT-lemma-1-15'*: $J = dg - 1 \implies dg > dh \vee H \neq 0 \implies \text{subresultant } (dg - 1) F G = \text{smult } ($
 $(-1)^{\wedge}(df - dg + 1) * \text{lead-coeff } G^{\wedge} (df - dg + 1)) H$
<proof>

lemmas *BT-lemma-1-13* = *BT-lemma-1-13'*[*OF - - - refl*]

lemmas *BT-lemma-1-15* = *BT-lemma-1-15'*[*OF - - - refl*]

lemma *subresultant-product*: **fixes** $F :: 'a :: \text{idom poly}$
assumes $F = B * G$
and *FG*: $\text{degree } F \geq \text{degree } G$
shows $\text{subresultant } J F G = (\text{if } J < \text{degree } G \text{ then } 0 \text{ else}$
 $\text{if } J < \text{degree } F \text{ then } \text{smult } (\text{lead-coeff } G^{\wedge} (\text{degree } F - J - 1)) G \text{ else } 1)$
<proof>

lemma *resultant-pseudo-mod-0*: **assumes** $\text{pseudo-mod } fg = (0 :: 'a :: \text{idom-divide poly})$
and *dfg*: $\text{degree } f \geq \text{degree } g$
and *f*: $f \neq 0$ **and** *g*: $g \neq 0$
shows $\text{resultant } fg = (\text{if } \text{degree } g = 0 \text{ then } \text{lead-coeff } g^{\wedge} \text{degree } f \text{ else } 0)$
<proof>

locale *primitive-remainder-sequence* =
fixes $F :: \text{nat} \Rightarrow 'a :: \text{idom-divide poly}$
and $n :: \text{nat} \Rightarrow \text{nat}$
and $\delta :: \text{nat} \Rightarrow \text{nat}$
and $f :: \text{nat} \Rightarrow 'a$
and $k :: \text{nat}$
and $\beta :: \text{nat} \Rightarrow 'a$
assumes $f: \bigwedge i. f i = \text{lead-coeff } (F i)$
and $n: \bigwedge i. n i = \text{degree } (F i)$
and $\delta: \bigwedge i. \delta i = n i - n (\text{Suc } i)$
and $n12: n 1 \geq n 2$
and $F12: F 1 \neq 0 F 2 \neq 0$
and $F0: \bigwedge i. i \neq 0 \implies F i = 0 \iff i > k$
and $\beta0: \bigwedge i. \beta i \neq 0$
and $\text{pmod}: \bigwedge i. i \geq 3 \implies i \leq \text{Suc } k \implies \text{smult } (\beta i) (F i) = \text{pseudo-mod } (F (i - 2)) (F (i - 1))$
begin

lemma *f10*: $f 1 \neq 0$ **and** *f20*: $f 2 \neq 0$ *<proof>*

lemma *f0*: $i \neq 0 \implies f i = 0 \iff i > k$
<proof>

lemma *n-gt*: **assumes** $2 \leq i i < k$

shows $n\ i > n\ (Suc\ i)$
 ⟨*proof*⟩

lemma *n-ge*: **assumes** $1 \leq i\ i < k$
shows $n\ i \geq n\ (Suc\ i)$
 ⟨*proof*⟩

lemma *n-ge-trans*: **assumes** $1 \leq i\ i \leq j\ j \leq k$
shows $n\ i \geq n\ j$
 ⟨*proof*⟩

lemma *delta-gt*: **assumes** $2 \leq i\ i < k$
shows $\delta\ i > 0$ ⟨*proof*⟩

lemma *k2:2 ≤ k*
 ⟨*proof*⟩

lemma *k0: k ≠ 0* ⟨*proof*⟩

lemma *ni2:3 ≤ i ⇒ i ≤ k ⇒ n i ≠ n 2*
 ⟨*proof*⟩
end

locale *subresultant-prs-locale* = *primitive-remainder-sequence* $F\ n\ \delta\ f\ k\ \beta$ **for**

$F :: nat \Rightarrow 'a :: idom-divide\ fract\ poly$

and $n :: nat \Rightarrow nat$

and $\delta :: nat \Rightarrow nat$

and $f :: nat \Rightarrow 'a\ fract$

and $k :: nat$

and $\beta :: nat \Rightarrow 'a\ fract\ +$

fixes $G1\ G2 :: 'a\ poly$

assumes $F1: F\ 1 = map-poly\ to-fract\ G1$

and $F2: F\ 2 = map-poly\ to-fract\ G2$

begin

definition $\alpha\ i = (f\ (i - 1)) \wedge (Suc\ (\delta\ (i - 2)))$

lemma $\alpha0: i > 1 \Rightarrow \alpha\ i = 0 \iff (i - 1) > k$
 ⟨*proof*⟩

lemma *α-char*:

assumes $3 \leq i\ i < k + 2$

shows $\alpha\ i = (f\ (i - 1)) \wedge (Suc\ (length\ (coeffs\ (F\ (i - 2)))) - length\ (coeffs\ (F\ (i - 1))))$

⟨*proof*⟩

definition $Q :: \text{nat} \Rightarrow 'a \text{ fract poly}$ **where**

$$Q \ i \equiv \text{smult } (\alpha \ i) \ (\text{fst } (\text{pdivmod } (F \ (i - 2)) \ (F \ (i - 1))))$$

lemma *beta-F-as-sum*:

assumes $3 \leq i \leq \text{Suc } k$

shows $\text{smult } (\beta \ i) \ (F \ i) = \text{smult } (\alpha \ i) \ (F \ (i - 2)) + - \ Q \ i * F \ (i - 1)$ (**is** ?t1)

<proof>

lemma **assumes** $3 \leq i \leq k$ **shows**

BT-lemma-2-21: $j < n \ i \implies \text{smult } (\alpha \ i \wedge (n \ (i - 1) - j)) \ (\text{subresultant } j \ (F \ (i - 2)) \ (F \ (i - 1)))$

$= \text{smult } ((-1) \wedge ((n \ (i - 2) - j) * (n \ (i - 1) - j)) * (f \ (i - 1)) \wedge (\delta \ (i - 2) + \delta \ (i - 1))) * (\beta \ i) \wedge (n \ (i - 1) - j)) \ (\text{subresultant } j \ (F \ (i - 1)) \ (F \ i))$

(**is** \implies ?eq-21) **and**

BT-lemma-2-22: $\text{smult } (\alpha \ i \wedge (\delta \ (i - 1))) \ (\text{subresultant } (n \ i) \ (F \ (i - 2)) \ (F \ (i - 1)))$

$= \text{smult } ((-1) \wedge ((\delta \ (i - 2) + \delta \ (i - 1)) * \delta \ (i - 1)) * f \ (i - 1) \wedge (\delta \ (i - 2) + \delta \ (i - 1))) * f \ i \wedge (\delta \ (i - 1) - 1) * (\beta \ i) \wedge \delta \ (i - 1)) \ (F \ i)$

(**is** ?eq-22) **and**

BT-lemma-2-23: $n \ i < j \implies j < n \ (i - 1) - 1 \implies \text{subresultant } j \ (F \ (i - 2)) \ (F \ (i - 1)) = 0$

(**is** \implies \implies ?eq-23) **and**

BT-lemma-2-24: $\text{smult } (\alpha \ i) \ (\text{subresultant } (n \ (i - 1) - 1) \ (F \ (i - 2)) \ (F \ (i - 1)))$

$= \text{smult } ((-1) \wedge (\delta \ (i - 2) + 1) * f \ (i - 1) \wedge (\delta \ (i - 2) + 1) * \beta \ i) \ (F \ i)$ (**is** ?eq-24)

<proof>

lemma *BT-eq-30*: $3 \leq i \implies i \leq k + 1 \implies j < n \ (i - 1) \implies$

$\text{smult } (\prod l \leftarrow [3..<i]. \alpha \ l \wedge (n \ (l - 1) - j)) \ (\text{subresultant } j \ (F \ 1) \ (F \ 2))$

$= \text{smult } (\prod l \leftarrow [3..<i]. \beta \ l \wedge (n \ (l - 1) - j) * f \ (l - 1) \wedge (\delta \ (l - 2) + \delta \ (l - 1)))$

$* (-1) \wedge ((n \ (l - 2) - j) * (n \ (l - 1) - j)) \ (\text{subresultant } j \ (F \ (i - 2)) \ (F \ (i - 1)))$

<proof>

lemma *nonzero-alphaprod*: **assumes** $i \leq k + 1$ **shows** $(\prod l \leftarrow [3..<i]. \alpha \ l \wedge (p \ l)) \neq 0$

<proof>

lemma *BT-eq-30'*: **assumes** $i: 3 \leq i \leq k + 1 \ j < n \ (i - 1)$

shows $\text{subresultant } j \ (F \ 1) \ (F \ 2)$

$= \text{smult } ((-1) \wedge (\sum l \leftarrow [3..<i]. (n \ (l - 2) - j) * (n \ (l - 1) - j)))$

$* (\prod l \leftarrow [3..<i]. (\beta \ l / \alpha \ l) \wedge (n \ (l - 1) - j)) * (\prod l \leftarrow [3..<i]. f \ (l - 1) \wedge (\delta \ (l - 2) + \delta \ (l - 1))) \ (\text{subresultant } j \ (F \ (i - 2)) \ (F \ (i - 1)))$

(**is** $= \text{smult } (?mm * ?b * ?f) -$)

<proof>

For defining the subresultant PRS, we mainly follow Brown's "The Sub-

resultant PRS Algorithm” (B).

definition $R j = (if j = n \ 2 \ then \ sdiv\text{-}poly \ (smult \ ((lead\text{-}coeff \ G2) \wedge (\delta \ 1)) \ G2) \ (lead\text{-}coeff \ G2) \ else \ subresultant \ j \ G1 \ G2)$

abbreviation $ff \ i \equiv \ to\text{-}fract \ (i \ :: \ 'a)$

abbreviation $ffp \equiv \ map\text{-}poly \ ff$

sublocale $map\text{-}poly\text{-}hom: \ map\text{-}poly\text{-}inj\text{-}idom\text{-}hom \ to\text{-}fract \langle proof \rangle$

definition $\sigma \ i = (\sum \ l \leftarrow [3..<Suc \ i]. \ (n \ (l - 2) + n \ (i - 1) + 1) * (n \ (l - 1) + n \ (i - 1) + 1))$

definition $\tau \ i = (\sum \ l \leftarrow [3..<Suc \ i]. \ (n \ (l - 2) + n \ i) * (n \ (l - 1) + n \ i))$

definition $\gamma \ i = (-1) \wedge (\sigma \ i) * pow\text{-}int \ (f \ (i - 1)) \ (1 - int \ (\delta \ (i - 1))) * (\prod \ l \leftarrow [3..<Suc \ i].$

$(\beta \ l / \alpha \ l) \wedge (n \ (l - 1) - n \ (i - 1) + 1) * (f \ (l - 1)) \wedge (\delta \ (l - 2) + \delta \ (l - 1)))$

definition $\Theta \ i = (-1) \wedge (\tau \ i) * pow\text{-}int \ (f \ i) \ (int \ (\delta \ (i - 1)) - 1) * (\prod \ l \leftarrow [3..<Suc \ i].$

$(\beta \ l / \alpha \ l) \wedge (n \ (l - 1) - n \ i) * (f \ (l - 1)) \wedge (\delta \ (l - 2) + \delta \ (l - 1)))$

lemma *fundamental-theorem-eq-4*: **assumes** $i: \ 3 \leq i \ i \leq k$

shows $ffp \ (R \ (n \ (i - 1) - 1)) = smult \ (\gamma \ i) \ (F \ i)$

$\langle proof \rangle$

lemma *fundamental-theorem-eq-5*: **assumes** $i: \ 3 \leq i \ i \leq k \ n \ i < j \ j < n \ (i - 1) - 1$

shows $R \ j = 0$

$\langle proof \rangle$

lemma *fundamental-theorem-eq-6*: **assumes** $3 \leq i \ i \leq k$ **shows** $ffp \ (R \ (n \ i)) = smult \ (\Theta \ i) \ (F \ i)$

(**is** ?lhs=?rhs)

$\langle proof \rangle$

lemma *fundamental-theorem-eq-7*: **assumes** $j: \ j < n \ k$ **shows** $R \ j = 0$

$\langle proof \rangle$

definition $G \ i = R \ (n \ (i - 1) - 1)$

definition $H \ i = R \ (n \ i)$

lemma *gamma-delta-beta-3*: $\gamma \ 3 = (-1) \wedge (\delta \ 1 + 1) * \beta \ 3$

$\langle proof \rangle$

fun $h :: \text{nat} \Rightarrow 'a \text{ fract}$ **where**
 $h\ i = (\text{if } (i \leq 1) \text{ then } 1 \text{ else if } i = 2 \text{ then } (f\ 2 \wedge \delta\ 1) \text{ else } (f\ i \wedge \delta\ (i - 1) / (h\ (i - 1) \wedge (\delta\ (i - 1) - 1))))$

lemma *smult-inverse-sdiv-poly*: **assumes** $\text{ffp}: p \in \text{range ffp}$
and $p: p = \text{smult } (\text{inverse } x) \ q$
and $p': p' = \text{sdiv-poly } q' \ x'$
and $xx: x = \text{ff } x'$
and $qq: q = \text{ffp } q'$
shows $p = \text{ffp } p'$
 $\langle \text{proof} \rangle$

end

locale *subresultant-prs-locale2* = *subresultant-prs-locale* $F\ n\ \delta\ f\ k\ \beta\ G1\ G2$ **for**
 $F :: \text{nat} \Rightarrow 'a :: \text{idom-divide fract poly}$
and $n :: \text{nat} \Rightarrow \text{nat}$
and $\delta :: \text{nat} \Rightarrow \text{nat}$
and $f :: \text{nat} \Rightarrow 'a \text{ fract}$
and $k :: \text{nat}$
and $\beta :: \text{nat} \Rightarrow 'a \text{ fract}$
and $G1\ G2 :: 'a \text{ poly} +$
assumes $\beta\ 3: \beta\ 3 = (-1) \wedge (\delta\ 1 + 1)$
and $\beta\ i: \bigwedge i. 4 \leq i \implies i \leq \text{Suc } k \implies \beta\ i = (-1) \wedge (\delta\ (i - 2) + 1) * f\ (i - 2)$
 $* h\ (i - 2) \wedge (\delta\ (i - 2))$
begin

lemma *B-eq-17-main*: $2 \leq i \implies i \leq k \implies$
 $h\ i = (-1) \wedge (n\ 1 + n\ i + i + 1) / f\ i$
 $* (\prod l \leftarrow [3.. < \text{Suc } (\text{Suc } i)]. (\alpha\ l / \beta\ l)) \wedge h\ i \neq 0$
 $\langle \text{proof} \rangle$

lemma *B-eq-17*: $2 \leq i \implies i \leq k \implies$
 $h\ i = (-1) \wedge (n\ 1 + n\ i + i + 1) / f\ i * (\prod l \leftarrow [3.. < \text{Suc } (\text{Suc } i)]. (\alpha\ l / \beta\ l))$
 $\langle \text{proof} \rangle$

lemma *B-theorem-2*: $3 \leq i \implies i \leq \text{Suc } k \implies \gamma\ i = 1$
 $\langle \text{proof} \rangle$

context

fixes $i :: \text{nat}$
assumes $i: 3 \leq i \leq k$

begin

lemma *B-theorem-3-b*: $\Theta\ i * f\ i = \text{ff } (\text{lead-coeff } (H\ i))$
 $\langle \text{proof} \rangle$

lemma *B-theorem-3-main*: $\Theta\ i * f\ i / \gamma\ (i + 1) = (-1) \wedge (n\ 1 + n\ i + i + 1) /$
 $f\ i * (\prod l \leftarrow [3.. < \text{Suc } (\text{Suc } i)]. (\alpha\ l / \beta\ l))$
 $\langle \text{proof} \rangle$

lemma *B-theorem-3*: $h\ i = \Theta\ i * f\ i\ h\ i = \text{ff}\ (\text{lead-coeff}\ (H\ i))$
 ⟨*proof*⟩
end

lemma *h0*: $i \leq k \implies h\ i \neq 0$
 ⟨*proof*⟩

lemma *deg-G12*: $\text{degree}\ G1 \geq \text{degree}\ G2$ ⟨*proof*⟩

lemma *R0*: **shows** $R\ 0 = [\text{: resultant}\ G1\ G2\ :]$
 ⟨*proof*⟩

context

fixes *div-exp* :: 'a \Rightarrow 'a \Rightarrow nat \Rightarrow 'a

assumes *div-exp*: $\bigwedge\ x\ y\ n.$

$(\text{to-fract}\ x)^{\wedge}n / (\text{to-fract}\ y)^{\wedge}(n-1) \in \text{range}\ \text{to-fract}$

$\implies \text{to-fract}\ (\text{div-exp}\ x\ y\ n) = (\text{to-fract}\ x)^{\wedge}n / (\text{to-fract}\ y)^{\wedge}(n-1)$

begin

lemma *subresultant-prs-main*: **assumes** *subresultant-prs-main* *div-exp* $G_{i-1}\ G_i\ h_{i-1}$
 $= (G_k, h_k)$

and $F\ i = \text{ffp}\ G_i$

and $F\ (i - 1) = \text{ffp}\ G_{i-1}$

and $h\ (i - 1) = \text{ff}\ h_{i-1}$

and $i \geq 3\ i \leq k$

shows $F\ k = \text{ffp}\ G_k \wedge h\ k = \text{ff}\ h_k \wedge (\forall\ j. i \leq j \longrightarrow j \leq k \longrightarrow F\ j \in \text{range}\ \text{ffp}$
 $\wedge \beta\ (\text{Suc}\ j) \in \text{range}\ \text{ff})$

⟨*proof*⟩

lemma *subresultant-prs*: **assumes** *res*: *subresultant-prs* *div-exp* $G1\ G2 = (Gk, hk)$

shows $F\ k = \text{ffp}\ Gk \wedge h\ k = \text{ff}\ hk \wedge (i \neq 0 \longrightarrow F\ i \in \text{range}\ \text{ffp}) \wedge (3 \leq i \longrightarrow$
 $i \leq \text{Suc}\ k \longrightarrow \beta\ i \in \text{range}\ \text{ff})$

⟨*proof*⟩

lemma *resultant-impl-main*: *resultant-impl-main* *div-exp* $G1\ G2 = \text{resultant}\ G1\ G2$

⟨*proof*⟩

end

end

At this point, we have soundness of the resultant-implementation, provided that we can instantiate the locale by constructing suitable values of F , b , h , etc. Now we show the existence of suitable locale parameters by constructively computing them.

context

fixes $G1\ G2 :: 'a :: \text{idom-divide}\ \text{poly}$

begin

private function F **and** b **and** h **where** $F\ i = (\text{if}\ i = (0 :: \text{nat})\ \text{then}\ 1$

```

else if i = 1 then map-poly to-fract G1 else if i = 2 then map-poly to-fract G2
else (let G = pseudo-mod (F (i - 2)) (F (i - 1))
in if F (i - 1) = 0 ∨ G = 0 then 0 else smult (inverse (b i)) G)
| b i = (if i ≤ 2 then 1 else
if i = 3 then (- 1) ^ (degree (F 1) - degree (F 2) + 1)
else if F (i - 2) = 0 then 1 else (- 1) ^ (degree (F (i - 2)) - degree (F (i - 1)) + 1) * lead-coeff (F (i - 2)) *
h (i - 2) ^ (degree (F (i - 2)) - degree (F (i - 1))))
| h i = (if (i ≤ 1) then 1 else if i = 2 then (lead-coeff (F 2) ^ (degree (F 1) - degree (F 2))) else
if F i = 0 then 1 else (lead-coeff (F i) ^ (degree (F (i - 1)) - degree (F i)) /
(h (i - 1) ^ ((degree (F (i - 1)) - degree (F i)) - 1))))
⟨proof⟩
termination
⟨proof⟩

```

```

declare h.simps[simp del] b.simps[simp del] F.simps[simp del]

```

```

private lemma Fb0: assumes base: G1 ≠ 0 G2 ≠ 0
shows (F i = 0 → F (Suc i) = 0) ∧ b i ≠ 0 ∧ h i ≠ 0
⟨proof⟩ definition k = (LEAST i. F (Suc i) = 0)

```

```

private lemma k-exists: ∃ i. F (Suc i) = 0
⟨proof⟩ lemma k: F (Suc k) = 0 i < k ⇒ F (Suc i) ≠ 0
⟨proof⟩

```

```

lemma enter-subresultant-prs: assumes len: length (coeffs G1) ≥ length (coeffs G2)
and G2: G2 ≠ 0
shows ∃ F n d f k b. subresultant-prs-locale2 F n d f k b G1 G2
⟨proof⟩
end

```

Now we obtain the soundness lemma outside the locale.

```

context
fixes div-exp :: 'a :: idom-divide ⇒ 'a ⇒ nat ⇒ 'a
assumes div-exp: ∧ x y n.
(to-fract x) ^ n / (to-fract y) ^ (n-1) ∈ range to-fract
⇒ to-fract (div-exp x y n) = (to-fract x) ^ n / (to-fract y) ^ (n-1)
begin

```

```

lemma resultant-impl-main: assumes len: length (coeffs G1) ≥ length (coeffs G2)
shows resultant-impl-main div-exp G1 G2 = resultant G1 G2
⟨proof⟩

```

```

theorem resultant-impl-generic: resultant-impl-generic div-exp = resultant
⟨proof⟩
end

```

lemma *resultant-impl*[simp]: *resultant-impl* = *resultant*
 ⟨proof⟩

lemma *resultant-impl-idom-divide*[simp]: *resultant-impl-idom-divide* = *resultant*
 ⟨proof⟩

7.3 Code Equations

In the following code-equations, we only compute the required values, e.g., h_k is not required if $n_k > 0$, we compute $(-1)^{\dots} * \dots$ via a case-analysis, and we perform special cases for $\delta_i = 1$, which is the most frequent case.

partial-function(*tailrec*) *subresultant-prs-main-impl* **where**
subresultant-prs-main-impl f G_{i-1} G_i n_{i-1} d_{i-1} h_{i-2} = (let
 g_{i-1} = lead-coeff G_{i-1} ;
 n_i = degree G_i ;
 h_{i-1} = (if $d_{i-1} = 1$ then g_{i-1} else *dichotomous-Lazard* g_{i-1} h_{i-2} d_{i-1});
 d_i = $n_{i-1} - n_i$;
 p_{mod} = pseudo-mod G_{i-1} G_i
 in (if $p_{mod} = 0$ then f (G_i , (if $d_i = 1$ then lead-coeff G_i
 else *dichotomous-Lazard* (lead-coeff G_i) h_{i-1} d_i)) else
 let
 g_i = lead-coeff G_i ;
 divisor = $(-1)^{d_i + 1} * g_{i-1} * (h_{i-1}^{d_i})$;
 G_{i-p1} = sdiv-poly p_{mod} divisor
 in *subresultant-prs-main-impl* f G_i G_{i-p1} n_i d_i h_{i-1}))

definition *subresultant-prs-impl* **where**
 [code del]: *subresultant-prs-impl* f G_1 G_2 = (let
 p_{mod} = pseudo-mod G_1 G_2 ;
 n_2 = degree G_2 ;
 δ_{i-1} = (degree $G_1 - n_2$);
 g_2 = lead-coeff G_2 ;
 h_2 = $g_2^{\delta_{i-1}}$
 in if $p_{mod} = 0$ then f (G_2, h_2) else let
 G_3 = $(-1)^{\delta_{i-1} + 1} * p_{mod}$;
 g_3 = lead-coeff G_3 ;
 n_3 = degree G_3 ;
 d_2 = $n_2 - n_3$;
 p_{mod} = pseudo-mod G_2 G_3
 in if $p_{mod} = 0$ then f (G_3 , if $d_2 = 1$ then g_3 else *dichotomous-Lazard* g_3 h_2
 d_2)
 else let divisor = $(-1)^{d_2 + 1} * g_2 * h_2^{d_2}$; G_4 = sdiv-poly p_{mod}
 divisor
 in *subresultant-prs-main-impl* f G_3 G_4 n_3 d_2 h_2
)

lemma *subresultant-prs-impl*: *subresultant-prs-impl* f G_1 G_2 = f (*subresultant-prs*
dichotomous-Lazard G_1 G_2)
 ⟨proof⟩

definition [code del]:

resultant-impl-rec = subresultant-prs-main-impl ($\lambda (Gk,hk)$). if degree $Gk = 0$ then hk else 0)

definition [code del]:

resultant-impl-start = subresultant-prs-impl ($\lambda (Gk,hk)$). if degree $Gk = 0$ then hk else 0)

definition [code del]:

resultant-impl-Lazard = resultant-impl-main dichotomous-Lazard

lemma *resultant-impl-start-code*[code]:

```
resultant-impl-start G1 G2 =
  (let pmod = pseudo-mod G1 G2;
    n2 = degree G2;
    n1 = degree G1;
    g2 = lead-coeff G2;
    d1 = n1 - n2
    in if pmod = 0 then if n2 = 0 then if d1 = 0 then 1 else if d1 = 1 then g2
else g2 ^ d1 else 0
  else let
    G3 = if even d1 then - pmod else pmod;
    n3 = degree G3;
    pmod = pseudo-mod G2 G3
    in if pmod = 0
      then if n3 = 0 then
        let d2 = n2 - n3;
        g3 = lead-coeff G3
        in (if d2 = 1 then g3 else
            dichotomous-Lazard g3 (if d1 = 1 then g2 else g2 ^ d1) d2)
      else 0
    else let
      h2 = (if d1 = 1 then g2 else g2 ^ d1);
      d2 = n2 - n3;
      divisor = (if d2 = 1 then g2 * h2 else if even d2 then - g2
        * h2 ^ d2 else g2 * h2 ^ d2);
      G4 = sdiv-poly pmod divisor
      in resultant-impl-rec G3 G4 n3 d2 h2)
  <proof>
```

lemma *resultant-impl-rec-code*[code]:

```
resultant-impl-rec Gi-1 Gi ni-1 d1-1 hi-2 = (
  let ni = degree Gi;
  pmod = pseudo-mod Gi-1 Gi
  in
  if pmod = 0
  then if ni = 0
  then
  let
  d1 = ni-1 - ni;
```



```

      gi = lead-coeff Gi
      in if d1 = 1 then gi else
        let gi-1 = lead-coeff Gi-1;
            hi-1 = (if d1-1 = 1 then gi-1 else dichotomous-Lazard gi-1 hi-2 d1-1)
        in
          dichotomous-Lazard gi hi-1 d1
        else 0
      else let
        d1 = ni-1 - ni;
        gi-1 = lead-coeff Gi-1;
        hi-1 = (if d1-1 = 1 then gi-1 else dichotomous-Lazard gi-1 hi-2 d1-1);
        divisor = if d1 = 1 then gi-1 * hi-1 else if even d1 then - gi-1 * hi-1 ^
d1 else gi-1 * hi-1 ^ d1;
        Gi-p1 = sdiv-poly pmod divisor
        in resultant-impl-rec Gi Gi-p1 ni d1 hi-1)
    <proof>

```

lemma *resultant-impl-Lazard-code*[code]: *resultant-impl-Lazard G1 G2 =*
(if G2 = 0 then if degree G1 = 0 then 1 else 0
else resultant-impl-start G1 G2)
 <proof>

lemma *resultant-impl-code*[code]: *resultant-impl f g =*
(if length (coeffs f) ≥ length (coeffs g) then resultant-impl-Lazard f g
else let res = resultant-impl-Lazard g f in
if even (degree f) ∨ even (degree g) then res else - res)
 <proof>

lemma *resultant-code*[code]: *resultant f g = resultant-impl f g* <proof>

end

8 Computing the Gcd via the subresultant PRS

This theory now formalizes how the subresultant PRS can be used to calculate the gcd of two polynomials. Moreover, it proves the connection between resultants and gcd, namely that the resultant is 0 iff the degree of the gcd is non-zero.

theory *Subresultant-Gcd*

imports

Subresultant

Polynomial-Factorization.Missing-Polynomial-Factorial

begin

8.1 Algorithm

definition *gcd-impl-primitive* **where**

[code del]: $\text{gcd-impl-primitive } G1 \ G2 = \text{normalize } (\text{primitive-part } (\text{fst } (\text{subresultant-prs } \text{dichotomous-Lazard } G1 \ G2)))$

definition *gcd-impl-main* **where**

[code del]: $\text{gcd-impl-main } G1 \ G2 = (\text{if } G1 = 0 \text{ then } 0 \text{ else if } G2 = 0 \text{ then } \text{normalize } G1 \text{ else}$

$\text{smult } (\text{gcd } (\text{content } G1) (\text{content } G2))$
 $(\text{gcd-impl-primitive } (\text{primitive-part } G1) (\text{primitive-part } G2)))$

definition *gcd-impl* **where**

$\text{gcd-impl } f \ g = (\text{if } \text{length } (\text{coeffs } f) \geq \text{length } (\text{coeffs } g) \text{ then } \text{gcd-impl-main } f \ g \text{ else } \text{gcd-impl-main } g \ f)$

8.2 Soundness Proof for $\text{gcd-impl} = \text{gcd}$

locale *subresultant-prs-gcd* = *subresultant-prs-locale2* $F \ n \ \delta \ f \ k \ \beta \ G1 \ G2$ **for**

$F :: \text{nat} \Rightarrow 'a :: \{\text{factorial-ring-gcd, semiring-gcd-mult-normalize}\} \text{ fract poly}$
and $n :: \text{nat} \Rightarrow \text{nat}$
and $\delta :: \text{nat} \Rightarrow \text{nat}$
and $f :: \text{nat} \Rightarrow 'a \text{ fract}$
and $k :: \text{nat}$
and $\beta :: \text{nat} \Rightarrow 'a \text{ fract}$
and $G1 \ G2 :: 'a \text{ poly}$

begin

The subresultant PRS computes the gcd up to a scalar multiple.

lemma *subresultant-prs-gcd*: **assumes** *subresultant-prs dichotomous-Lazard* $G1 \ G2 = (Gk, hk)$

shows $\exists a \ b. a \neq 0 \wedge b \neq 0 \wedge \text{smult } a \ (\text{gcd } G1 \ G2) = \text{smult } b \ (\text{normalize } Gk)$
 $\langle \text{proof} \rangle$

lemma *gcd-impl-primitive*: **assumes** *primitive-part* $G1 = G1$ **and** *primitive-part* $G2 = G2$

shows $\text{gcd-impl-primitive } G1 \ G2 = \text{gcd } G1 \ G2$

$\langle \text{proof} \rangle$

end

lemma *gcd-impl-main*: **assumes** *len*: $\text{length } (\text{coeffs } G1) \geq \text{length } (\text{coeffs } G2)$

shows $\text{gcd-impl-main } G1 \ G2 = \text{gcd } G1 \ G2$

$\langle \text{proof} \rangle$

theorem *gcd-impl[simp]*: $\text{gcd-impl} = \text{gcd}$

$\langle \text{proof} \rangle$

The implementation also reveals an important connection between resultant and gcd.

lemma *resultant-0-gcd*: $\text{resultant } f \ g = 0 \iff \text{degree } (\text{gcd } f \ g) \neq 0$

$\langle \text{proof} \rangle$

8.3 Code Equations

definition [code del]:

gcd-impl-rec = subresultant-prs-main-impl fst

definition [code del]:

gcd-impl-start = subresultant-prs-impl fst

lemma *gcd-impl-rec-code*[code]:

gcd-impl-rec Gi-1 Gi ni-1 d1-1 hi-2 = (
let pmod = pseudo-mod Gi-1 Gi
in
if pmod = 0 then Gi
else let
ni = degree Gi;
d1 = ni-1 - ni;
gi-1 = lead-coeff Gi-1;
hi-1 = (if d1-1 = 1 then gi-1 else dichotomous-Lazard gi-1 hi-2 d1-1);
*divisor = if d1 = 1 then gi-1 * hi-1 else if even d1 then - gi-1 * hi-1 ^*
*d1 else gi-1 * hi-1 ^ d1;*
Gi-p1 = sdiv-poly pmod divisor
in gcd-impl-rec Gi Gi-p1 ni d1 hi-1)
<proof>

lemma *gcd-impl-start-code*[code]:

gcd-impl-start G1 G2 =
(let pmod = pseudo-mod G1 G2
in if pmod = 0 then G2
else let
n2 = degree G2;
n1 = degree G1;
d1 = n1 - n2;
G3 = if even d1 then - pmod else pmod;
pmod = pseudo-mod G2 G3
in if pmod = 0
then G3
else let
g2 = lead-coeff G2;
n3 = degree G3;
h2 = (if d1 = 1 then g2 else g2 ^ d1);
d2 = n2 - n3;
*divisor = (if d2 = 1 then g2 * h2 else if even d2 then - g2*
** h2 ^ d2 else g2 * h2 ^ d2);*
G4 = sdiv-poly pmod divisor
in gcd-impl-rec G3 G4 n3 d2 h2)
<proof>

lemma *gcd-impl-main-code*[code]:

gcd-impl-main G1 G2 = (if G1 = 0 then 0 else if G2 = 0 then normalize G1 else
let c1 = content G1;
c2 = content G2;

```

    p1 = map-poly (λ x. x div c1) G1;
    p2 = map-poly (λ x. x div c2) G2
    in smult (gcd c1 c2) (normalize (primitive-part (gcd-impl-start p1 p2))))
  ⟨proof⟩

```

corollary *gcd-via-subresultant*: $\text{gcd } f \ g = \text{gcd-impl } f \ g$ ⟨proof⟩

Note that we did not activate $\text{gcd } ?f \ ?g = \text{gcd-impl } ?f \ ?g$ as code-equation, since according to our experiments, the subresultant-gcd algorithm is not always more efficient than the currently active equation. In particular, on *int poly gcd-impl* performs worse, but on multi-variate polynomials, e.g., *int poly poly poly*, *gcd-impl* is preferable.

end

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