

A verified factorization algorithm for integer polynomials with polynomial complexity*

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Abstract

Short vectors in lattices and factors of integer polynomials are related. Each factor of an integer polynomial belongs to a certain lattice. When factoring polynomials, the condition that we are looking for an irreducible polynomial means that we must look for a *small* element in a lattice, which can be done by a basis reduction algorithm. In this development we formalize this connection and thereby one main application of the LLL basis reduction algorithm: an algorithm to factor square-free integer polynomials which runs in polynomial time. The work is based on our previous Berlekamp–Zassenhaus development, where the exponential reconstruction phase has been replaced by the polynomial-time basis reduction algorithm. Thanks to this formalization we found a serious flaw in a textbook.

Contents

1	Introduction	2
2	Factor bound	5
3	Executable <i>dvdm</i> operation	5
3.1	Uniqueness of division algorithm for polynomials	6
3.2	Executable division operation modulo m for polynomials . . .	7
4	The LLL factorization algorithm	8
5	Correctness of the LLL factorization algorithm	10
5.1	Basic facts about the auxiliary functions	10
5.2	Facts about Sylvester matrices and norms	11

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5.3	Proof of the key lemma 16.20	12
5.4	Properties of the computed lattice and its connection with Sylvester matrices	12
5.5	Proving that <i>factorization-lattice</i> returns a basis of the lattice	13
5.6	Being in the lattice is being a multiple modulo	13
5.7	Soundness of the LLL factorization algorithm	14
6	Calculating All Possible Sums of Sub-Multisets	16
7	Implementation and soundness of a modified version of Al- gorithm 16.22	17
7.1	Previous lemmas obtained using local type definitions	17
7.2	The modified version of Algorithm 16.22	17
7.3	Soundness proof	20
7.3.1	Starting the proof	20
7.3.2	Inner loop	22
7.3.3	Outer loop	25
7.3.4	Final statement	26
8	Mistakes in the textbook Modern Computer Algebra (2nd edition)	26
8.1	A real problem of Algorithm 16.22	27
8.2	Another potential problem of Algorithm 16.22	27
8.3	Verified wrong results	28

1 Introduction

In order to factor an integer polynomial f , we may assume a *modular* factorization of f into several monic factors u_i : $f \equiv \text{lc}(f) \cdot \prod_i u_i$ modulo m where $m = p^l$ is some prime power for user-specified l . In Isabelle, we just reuse our verified modular factorization algorithm [1] to obtain the modular factorization of f .

We briefly explain how to compute non-trivial integer factors of f . The key is the following lemma [2, Lemma 16.20].

Lemma 1 ([2, Lemma 16.20]) *Let f, g, u be non-constant integer polynomials. Let u be monic. If u divides f modulo m , u divides g modulo m , and $\|f\|^{degree(g)} \cdot \|g\|^{degree(f)} < m$, then $h = \text{gcd}(f, g)$ is non-constant.*

Let f be a polynomial of degree n . Let u be any degree- d factor of f modulo m . Now assume that f is reducible, so $f = f_1 \cdot f_2$ where w.l.o.g., we assume that u divides f_1 modulo m and that $0 < degree(f_1) < n$. Let us further assume that a lattice $L_{u,k}$ encodes the set of all polynomials of

degree below $d + k$ (as vectors of length $d + k$) which are divisible by u modulo m . Fix $k = n - d$. Then clearly, $f_1 \in L_{u,k}$.

In order to instantiate Lemma 1, it now suffices to take g as the polynomial corresponding to any short vector in $L_{u,k}$: u will divide g modulo m by definition of $L_{u,k}$ and moreover $\text{degree}(g) < n$. The short vector requirement will provide an upper bound to satisfy the assumption $\|f\|^{\text{degree}(g)} \cdot \|g\|^{\text{degree}(f)} < m$.

$$\|g\| \leq 2^{(n-1)/2} \cdot \|f_1\| \leq 2^{(n-1)/2} \cdot 2^{n-1} \|f\| = 2^{3(n-1)/2} \|f\| \quad (1)$$

$$\|f\|^{\text{degree}(g)} \cdot \|g\|^{\text{degree}(f)} \leq \|f\|^{n-1} \cdot (2^{3(n-1)/2} \|f\|)^n = \|f\|^{2n-1} \cdot 2^{3n(n-1)/2} \quad (2)$$

Here, the first inequality in (1) is the short vector approximation ($f_1 \in L_{u,k}$). The second inequality in (1) is Mignotte's factor bound (f_1 is a factor of f). Finally, (1) is used as an approximation of $\|g\|$ in (2).

Hence, if l is chosen large enough so that $m = p^l > \|f\|^{2n-1} \cdot 2^{3n(n-1)/2}$ then all preconditions of Lemma 1 are satisfied, and $h = \text{gcd}(f, g)$ will be a non-constant factor of f . Since the degree of h will be strictly less than n , h is also a proper factor of f , i.e., in particular $h \notin \{1, f\}$.

The textbook [2] also describes the general idea of the factorization algorithm based on the previous lemma in prose, and then presents an algorithm in pseudo-code which slightly extends the idea by directly splitting off *irreducible* factors [2, Algorithm 16.22]. We initially implemented and tried to verify this pseudo-code algorithm (see files `Factorization_Algorithm_16_22.thy` and `Modern_Computer_Algebra_Problem.thy`). After some work, we had only one remaining goal to prove: the content of the polynomial g corresponding to the short vector is not divisible by the chosen prime p . However, we were unable to figure out how to discharge this goal and then also started to search for inputs where the algorithm delivers wrong results. After a while we realized that Algorithm 16.22 indeed has a serious flaw as demonstrated in the upcoming example.

Example 1 Consider the square-free and content-free polynomial $f = (1 + x) \cdot (1 + x + x^3)$. Then according to Algorithm 16.22 we determine

- the prime $p = 2$
- the exponent $l = 61$
(our new formalized algorithm uses a tighter bound which results in $l = 41$)
- the leading coefficient $b = 1$
- the value $B = 96$
- the factorization mod p via $h_1 = 1 + x$, $h_2 = 1 + x + x^3$

- the factorization mod p^l via $g_1 = 1 + x$, $g_2 = 1 + x + x^3$
- $f^* = f$, $T = \{1, 2\}$, $G = \emptyset$.
- we enter the loop and in the first iteration choose
- $u = 1 + x + x^3$, $d = 3$, $j = 4$
- we consider the lattice generated by $(1, 1, 0, 1)$, $(p^l, 0, 0, 0)$, $(0, p^l, 0, 0)$, $(0, 0, p^l, 0)$.
- now we obtain a short vector in the lattice: $g^* = (2, 2, 0, 2)$.
Note that g^* has not really been computed by Algorithm 16.10, but it satisfies the soundness criterion, i.e., it is a sufficiently short vector in the lattice.

To see this, note that a shortest vector in the lattice is $(1, 1, 0, 1)$.

$$\|g^*\| = 2 \cdot \sqrt{3} \leq 2 \cdot \sqrt{2} \cdot \sqrt{3} = 2^{(j-1)/2} \cdot \|(1, 1, 0, 1)\|$$

So g^* has the required precision that was assumed by the short-vector calculation.

- the problem at this point is that p divides the content of g^* . Consequently, every polynomial divides $g^* \bmod p$. Thus in step 9 we compute $S = T$, $h = 1$, enter the then-branch and update $T = \emptyset$, $G = G \cup \{1 + x + x^3\}$, $f^* = 1$, $b = 1$.
- Then in step 10 we update $G = \{1 + x + x^3, 1\}$ and finally return that the factorization of f is $(1 + x + x^3) \cdot 1$.

More details about the bug and some other wrong results presented in the book are shown in the file `Modern_Computer_Algebra_Problem.thy`.

Once we realized the problem, we derived another algorithm based on Lemma 1, which also runs in polynomial-time, and prove its soundness in Isabelle/HOL. The corresponding Isabelle statement is as follows:

Theorem 1 (LLL Factorization Algorithm)

```

assumes square_free (f :: int poly)
and degree f ≠ 0
and LLL_factorization f = gs
shows f = prod_list gs
and ∀gi ∈ set gs. irreducible gi

```

Finally, we also have been able to fix Algorithm 16.22 and provide a formal correctness proof of the slightly modified version. It can be seen as an implementation of the pseudo-code factorization algorithm given by Lenstra, Lenstra, and Lovász [3].

2 Factor bound

This theory extends the work about factor bounds which was carried out in the Berlekamp-Zassenhaus development.

```
theory Factor-Bound-2
imports Berlekamp-Zassenhaus.Factor-Bound
         LLL-Basis-Reduction.Norms
begin
```

```
lemma norm-1-bound-mignotte:  $\text{norm1 } f \leq 2^{\wedge}(\text{degree } f) * \text{mahler-measure } f$ 
<proof>
```

```
lemma mahler-measure-l2norm:  $\text{mahler-measure } f \leq \text{sqrt } (\text{of-int } \|f\|^2)$ 
<proof>
```

```
lemma sq-norm-factor-bound:
  fixes  $f\ h :: \text{int poly}$ 
  assumes  $\text{dvd: } h \text{ dvd } f$  and  $\text{f0: } f \neq 0$ 
  shows  $\|h\|^2 \leq 2^{\wedge}(2 * \text{degree } h) * \|f\|^2$ 
<proof>
```

```
end
```

3 Executable dvdmod operation

This theory contains some results about division of integer polynomials which are not part of Polynomial_Factorization.Dvd_Int_Poly.thy.

Essentially, we give an executable implementation of division modulo m.

```
theory Missing-Dvd-Int-Poly
imports
  Berlekamp-Zassenhaus.Poly-Mod-Finite-Field
  Berlekamp-Zassenhaus.Polynomial-Record-Based
  Berlekamp-Zassenhaus.Hensel-Lifting
  Subresultants.Subresultant
  Perron-Frobenius.Cancel-Card-Constraint
begin
```

```
lemma degree-div-mod-smult:
  fixes  $g :: \text{int poly}$ 
  assumes  $g$ :  $\text{degree } g < j$ 
  and  $r$ :  $\text{degree } r < d$ 
  and  $u$ :  $\text{degree } u = d$ 
  and  $g1$ :  $g = q * u + \text{smult } m\ r$ 
  and  $q$ :  $q \neq 0$  and  $m\text{-not0}$ :  $m \neq 0$ 
shows  $\text{degree } q < j - d$ 
<proof>
```

3.1 Uniqueness of division algorithm for polynomials

lemma *uniqueness-algorithm-division-poly*:

fixes $f::'a::\{\text{comm-ring,semiring-1-no-zero-divisors}\}$ *poly*

assumes $f1: f = g * q1 + r1$

and $f2: f = g * q2 + r2$

and $g: g \neq 0$

and $r1: r1 = 0 \vee \text{degree } r1 < \text{degree } g$

and $r2: r2 = 0 \vee \text{degree } r2 < \text{degree } g$

shows $q1 = q2 \wedge r1 = r2$

<proof>

lemma *pdivmod-eq-pdivmod-monic*:

assumes $g: \text{monic } g$

shows $\text{pdivmod } f \ g = \text{pdivmod-monic } f \ g$

<proof>

context *poly-mod*

begin

definition $\text{pdivmod2 } f \ g = (\text{if } Mp \ g = 0 \text{ then } (0, f)$

else let $ilc = \text{inverse-p } m \ ((\text{lead-coeff } (Mp \ g)))$;

$h = \text{Polynomial.smult } ilc \ (Mp \ g)$; $(q, r) = \text{pseudo-divmod } (Mp \ f) \ (Mp \ h)$

in $(\text{Polynomial.smult } ilc \ q, r)$

end

context *poly-mod-prime-type*

begin

lemma *dvdm-iff-pdivmod0*:

assumes $f: (F :: 'a \text{ mod-ring } \text{poly}) = \text{of-int-poly } f$

and $g: (G :: 'a \text{ mod-ring } \text{poly}) = \text{of-int-poly } g$

shows $g \ \text{dvdm } f = (\text{snd } (\text{pdivmod } F \ G) = 0)$

<proof>

lemma *of-int-poly-Mp-0[simp]*: $(\text{of-int-poly } (Mp \ a) = (0:: 'a \text{ mod-ring } \text{poly})) =$
 $(Mp \ a = 0)$

<proof>

lemma *uniqueness-algorithm-division-of-int-poly*:

assumes $g0: Mp \ g \neq 0$

and $f: (F :: 'a \text{ mod-ring } \text{poly}) = \text{of-int-poly } f$

and $g: (G :: 'a \text{ mod-ring } \text{poly}) = \text{of-int-poly } g$

and $F: F = G * Q + R$

and $R: R = 0 \vee \text{degree } R < \text{degree } G$

and $Mp\text{-}f: Mp \ f = Mp \ g * q + r$

and $r: r = 0 \vee \text{degree } r < \text{degree } (Mp \ g)$

shows $Q = \text{of-int-poly } q \wedge R = \text{of-int-poly } r$

<proof>

corollary *uniqueness-algorithm-division-to-int-poly*:
assumes $g0: Mp\ g \neq 0$
and $f: (F :: 'a\ mod\ ring\ poly) = of-int-poly\ f$
and $g: (G :: 'a\ mod\ ring\ poly) = of-int-poly\ g$
and $F: F = G * Q + R$
and $R: R = 0 \vee degree\ R < degree\ G$
and $Mp-f: Mp\ f = Mp\ g * q + r$
and $r: r = 0 \vee degree\ r < degree\ (Mp\ g)$
shows $Mp\ q = to-int-poly\ Q \wedge Mp\ r = to-int-poly\ R$
 $\langle proof \rangle$

lemma *uniqueness-algorithm-division-Mp-Rel*:
assumes *monic-Mpg*: $monic\ (Mp\ g)$
and $f: (F :: 'a\ mod\ ring\ poly) = of-int-poly\ f$
and $g: (G :: 'a\ mod\ ring\ poly) = of-int-poly\ g$
and $qr: pseudo-divmod\ (Mp\ f)\ (Mp\ g) = (q,r)$
and $QR: pseudo-divmod\ F\ G = (Q,R)$
shows $MP-Rel\ q\ Q \wedge MP-Rel\ r\ R$
 $\langle proof \rangle$

definition *MP-Rel-Pair* $A\ B \equiv (let\ (a,b) = A; (c,d) = B\ in\ MP-Rel\ a\ c \wedge MP-Rel\ b\ d)$

lemma *pdivmod2-rel[transfer-rule]*:
 $(MP-Rel\ ==> MP-Rel\ ==> MP-Rel-Pair)\ (pdivmod2)\ (pdivmod)$
 $\langle proof \rangle$

3.2 Executable division operation modulo m for polynomials

lemma *dvdm-iff-Mp-pdivmod2*:
shows $g\ dvdm\ f = (Mp\ (snd\ (pdivmod2\ f\ g)) = 0)$
 $\langle proof \rangle$

end

lemmas **(in** *poly-mod-prime*) *dvdm-pdivmod* = *poly-mod-prime-type.dvdm-iff-Mp-pdivmod2*
 $[unfolded\ poly-mod-type-simps, internalize-sort\ 'a :: prime-card, OF\ type-to-set,$
 $unfolded\ remove-duplicate-premise, cancel-type-definition, OF\ non-empty]$

lemma **(in** *poly-mod*) *dvdm-code*:
 $g\ dvdm\ f = (if\ prime\ m\ then\ Mp\ (snd\ (pdivmod2\ f\ g)) = 0$
 $else\ Code.abort\ (STR\ "dvdm\ error: m\ is\ not\ a\ prime\ number")\ (\lambda\ -. g\ dvdm\ f))$
 $\langle proof \rangle$

declare *poly-mod.pdivmod2-def*[code]
declare *poly-mod.dvdm-code*[code]

end

4 The LLL factorization algorithm

This theory contains an implementation of a polynomial time factorization algorithm. It first constructs a modular factorization. Afterwards it recursively invokes the LLL basis reduction algorithm on one lattice to either split a polynomial into two non-trivial factors, or to deduce irreducibility.

theory *LLL-Factorization-Impl*

imports *LLL-Basis-Reduction.LLL-Certification*

Factor-Bound-2

Missing-Dvd-Int-Poly

Berlekamp-Zassenhaus.Berlekamp-Zassenhaus

begin

hide-const (**open**) *up-ring.coeff up-ring.monom*

Unique-Factorization.factors Divisibility.factors

Unique-Factorization.factor Divisibility.factor

Divisibility.prime

definition *factorization-lattice* **where** *factorization-lattice u k m* \equiv
 $\text{map } (\lambda i. \text{vec-of-poly-}n (u * \text{monom } 1 i) (\text{degree } u + k)) [k >..0]$ @
 $\text{map } (\lambda i. \text{vec-of-poly-}n (\text{monom } m i) (\text{degree } u + k)) [\text{degree } u >..0]$

fun *min-degree-poly* :: *int poly* \Rightarrow *int poly* \Rightarrow *int poly*

where *min-degree-poly a b* = (*if degree a* \leq *degree b* *then a* *else b*)

fun *choose-u* :: *int poly list* \Rightarrow *int poly*

where *choose-u []* = *undefined*

| *choose-u [gi]* = *gi*

| *choose-u (gi # gj # gs)* = *min-degree-poly gi (choose-u (gj # gs))*

lemma *factorization-lattice-code[code]*: *factorization-lattice u k m* = (

let n = degree u *in*

map

$(\lambda i. \text{vec-of-poly-}n (\text{monom-mult } i u) (n+k)) [k >..0]$

@ $\text{map } (\lambda i. \text{vec-of-poly-}n (\text{monom } m i) (n+k)) [n >..0]$

) *<proof>*

Optimization: directly try to minimize coefficients of polynomial *u*.

definition *LLL-short-polynomial* **where**

LLL-short-polynomial pl n u = *poly-of-vec (short-vector-hybrid 2 (factorization-lattice*

$(\text{poly-mod.inv-Mp } pl (\text{poly-mod.Mp } pl u)) (n - \text{degree } u) pl)$)

locale *LLL-implementation* =

fixes *p pl* :: *int*

begin

function *LLL-many-reconstruction* **where**

```
LLL-many-reconstruction f us = (let
  d = degree f;
  d2 = d div 2;
  f2-opt = find-map-filter
    (λ u. gcd f (LLL-short-polynomial pl (Suc d2) u))
    (λ f2. let deg = degree f2 in deg > 0 ∧ deg < d)
    (filter (λ u. degree u ≤ d2) us)
  in case f2-opt of None ⇒ [f]
  | Some f2 ⇒ let f1 = f div f2;
    (us1, us2) = List.partition (λ gi. poly-mod.dvdm p gi f1) us
    in LLL-many-reconstruction f1 us1 @ LLL-many-reconstruction f2 us2)
⟨proof⟩
```

termination

⟨proof⟩

function *LLL-reconstruction* **where**

```
LLL-reconstruction f us = (let
  d = degree f;
  u = choose-u us;
  g = LLL-short-polynomial pl d u;
  f2 = gcd f g;
  deg = degree f2
  in if deg = 0 ∨ deg ≥ d then [f]
  else let f1 = f div f2;
    (us1, us2) = List.partition (λ gi. poly-mod.dvdm p gi f1) us
    in LLL-reconstruction f1 us1 @ LLL-reconstruction f2 us2)
⟨proof⟩
```

termination

⟨proof⟩

end

declare *LLL-implementation.LLL-reconstruction.simps*[code]

declare *LLL-implementation.LLL-many-reconstruction.simps*[code]

definition *LLL-factorization* :: int poly ⇒ int poly list **where**

```
LLL-factorization f = (let
  — find suitable prime
  p = suitable-prime-bz f;
  — compute finite field factorization
  (–, fs) = finite-field-factorization-int p f;
  — determine exponent l and B
  n = degree f;
  no = ||f||2;
  B = sqrt-int-ceiling (25 * (n – 1) * (n – 1)) * no2 * (n – 1));
```

```

  l = find-exponent p B;
  — perform hensel lifting to lift factorization to mod  $p^l$ 
  us = hensel-lifting p l f fs;
  — reconstruct integer factors via LLL algorithm
  pl = pl
  in LLL-implementation.LLL-reconstruction p pl f us)

```

definition *LLL-many-factorization* :: *int poly* ⇒ *int poly list* **where**

```

  LLL-many-factorization f = (let
    — find suitable prime
    p = suitable-prime-bz f;
    — compute finite field factorization
    (·, fs) = finite-field-factorization-int p f;
    — determine exponent l and B
    n = degree f;
    no = ||f||2;
    B = sqrt-int-ceiling (2(5 * (n div 2) * (n div 2)) * no(2 * (n div 2)));
    l = find-exponent p B;
    — perform hensel lifting to lift factorization to mod  $p^l$ 
    us = hensel-lifting p l f fs;
    — reconstruct integer factors via LLL algorithm
    pl = pl
  in LLL-implementation.LLL-many-reconstruction p pl f us)

```

end

5 Correctness of the LLL factorization algorithm

This theory connects short vectors of lattices and factors of polynomials. From this connection, we derive soundness of the lattice based factorization algorithm.

theory *LLL-Factorization*

imports

LLL-Factorization-Impl

Berlekamp-Zassenhaus.Factorize-Int-Poly

begin

5.1 Basic facts about the auxiliary functions

hide-const (**open**) *module.smult*

lemma *nth-factorization-lattice*:

fixes *u* **and** *d*

defines $n \equiv \text{degree } u$

assumes $i < n + d$

shows *factorization-lattice* $u \ d \ m \ ! \ i =$

vec-of-poly-n (if $i < d$ then $u * \text{monom } 1 \ (d - \text{Suc } i)$ else $\text{monom } m \ (n+d-\text{Suc } i)$) $(n+d)$

<proof>

lemma *length-factorization-lattice*[simp]:
shows $\text{length } (\text{factorization-lattice } u \ d \ m) = \text{degree } u + d$
<proof>

lemma *dim-factorization-lattice*:
assumes $x < \text{degree } u + d$
shows $\text{dim-vec } (\text{factorization-lattice } u \ d \ m \ ! \ x) = \text{degree } u + d$
<proof>

lemma *dim-factorization-lattice-element*:
assumes $x \in \text{set } (\text{factorization-lattice } u \ d \ m)$ **shows** $\text{dim-vec } x = \text{degree } u + d$
<proof>

lemma *set-factorization-lattice-in-carrier*[simp]: $\text{set } (\text{factorization-lattice } u \ d \ m) \subseteq \text{carrier-vec } (\text{degree } u + d)$
<proof>

lemma *choose-u-Cons*: $\text{choose-u } (x\#xs) =$
 $(\text{if } xs = [] \text{ then } x \text{ else } \text{min-degree-poly } x \ (\text{choose-u } xs))$
<proof>

lemma *choose-u-member*: $xs \neq [] \implies \text{choose-u } xs \in \text{set } xs$
<proof>

declare *choose-u.simps*[simp del]

5.2 Facts about Sylvester matrices and norms

lemma (in *LLL*) *lattice-is-span* [simp]: $\text{lattice-of } xs = \text{span-list } xs$
<proof>

lemma *sq-norm-row-sylvester-mat1*:
fixes $f \ g :: 'a :: \text{conjugatable-ring poly}$
assumes $i: i < \text{degree } g$
shows $\|(\text{row } (\text{sylvester-mat } f \ g) \ i)\|^2 = \|f\|^2$
<proof>

lemma *sq-norm-row-sylvester-mat2*:
fixes $f \ g :: 'a :: \text{conjugatable-ring poly}$
assumes $i1: \text{degree } g \leq i$ **and** $i2: i < \text{degree } f + \text{degree } g$
shows $\|\text{row } (\text{sylvester-mat } f \ g) \ i\|^2 = \|g\|^2$
<proof>

lemma *Hadamard's-inequality-int*:
fixes $A::\text{int mat}$
assumes $A: A \in \text{carrier-mat } n \ n$

shows $|det A| \leq \text{sqrt} (\text{of-int} (\text{prod-list} (\text{map sq-norm} (\text{rows } A))))$
 ⟨proof⟩

lemma resultant-le-prod-sq-norm:

fixes $f g :: \text{int poly}$
defines $n \equiv \text{degree } f$ **and** $k \equiv \text{degree } g$
shows $|\text{resultant } f g| \leq \text{sqrt} (\text{of-int} (\|f\|^2 \wedge k * \|g\|^2 \wedge n))$
 ⟨proof⟩

5.3 Proof of the key lemma 16.20

lemma common-factor-via-short:

fixes $f g u :: \text{int poly}$
defines $n \equiv \text{degree } f$ **and** $k \equiv \text{degree } g$
assumes $n0: n > 0$ **and** $k0: k > 0$
and $\text{monic}: \text{monic } u$ **and** $\text{deg-u}: \text{degree } u > 0$
and $\text{uf}: \text{poly-mod.dvdm } m u f$ **and** $\text{ug}: \text{poly-mod.dvdm } m u g$
and $\text{short}: \|f\|^2 \wedge k * \|g\|^2 \wedge n < m^2$
and $m: m \geq 0$
shows $\text{degree} (\text{gcd } f g) > 0$
 ⟨proof⟩

5.4 Properties of the computed lattice and its connection with Sylvester matrices

lemma factorization-lattice-as-sylvester:

fixes $p :: 'a :: \text{semidom poly}$
assumes $dj: d \leq j$ **and** $d: \text{degree } p = d$
shows $\text{mat-of-rows } j (\text{factorization-lattice } p (j-d) m) = \text{sylvester-mat-sub } d (j-d) p [:m:]$
 ⟨proof⟩

context inj-comm-semiring-hom begin

lemma map-poly-hom-mult-monom [*hom-distrib*]:

$\text{map-poly hom} (p * \text{monom } a n) = \text{map-poly hom } p * \text{monom} (\text{hom } a) n$
 ⟨proof⟩

lemma hom-vec-of-poly-n [*hom-distrib*]:

$\text{map-vec hom} (\text{vec-of-poly-n } p n) = \text{vec-of-poly-n} (\text{map-poly hom } p) n$
 ⟨proof⟩

lemma hom-factorization-lattice [*hom-distrib*]:

shows $\text{map} (\text{map-vec hom}) (\text{factorization-lattice } u k m) = \text{factorization-lattice} (\text{map-poly hom } u) k (\text{hom } m)$
 ⟨proof⟩

end

5.5 Proving that *factorization-lattice* returns a basis of the lattice

context *LLL*
begin

sublocale *idom-vec n TYPE(int)* \langle *proof* \rangle

lemma *upper-triangular-factorization-lattice:*

fixes $u :: 'a :: \text{semidom poly}$ **and** $d :: \text{nat}$

assumes $d \leq n$ **and** $du: d = \text{degree } u$

shows *upper-triangular* (*mat-of-rows* n (*factorization-lattice* u ($n-d$) k))

(**is** *upper-triangular* $?M$)

\langle *proof* \rangle

lemma *factorization-lattice-diag-nonzero:*

fixes $u :: 'a :: \text{semidom poly}$ **and** d

assumes $d = \text{degree } u$

and $dn: d \leq n$

and $u: u \neq 0$

and $m0: k \neq 0$

and $i: i < n$

shows (*factorization-lattice* u ($n-d$) k) ! i \$ $i \neq 0$

\langle *proof* \rangle

corollary *factorization-lattice-diag-nonzero-RAT:* **fixes** d

assumes $d = \text{degree } u$

and $d \leq n$

and $u \neq 0$

and $k \neq 0$

and $i < n$

shows *RAT* (*factorization-lattice* u ($n-d$) k) ! i \$ $i \neq 0$

\langle *proof* \rangle

sublocale *gs: vec-space TYPE(rat) n* \langle *proof* \rangle

lemma *lin-indpt-list-factorization-lattice:* **fixes** d

assumes $d: d = \text{degree } u$ **and** $dn: d \leq n$ **and** $u: u \neq 0$ **and** $k: k \neq 0$

shows *gs.lin-indpt-list* (*RAT* (*factorization-lattice* u ($n-d$) k)) (**is** *gs.lin-indpt-list* (*RAT* $?vs$))

\langle *proof* \rangle

end

5.6 Being in the lattice is being a multiple modulo

lemma (**in** *semiring-hom*) *hom-poly-of-vec: map-poly hom (poly-of-vec v) = poly-of-vec (map-vec hom v)*

\langle *proof* \rangle

abbreviation *of-int-vec* \equiv *map-vec of-int*

context *LLL*
begin

lemma *lincomb-to-dvd-modulo*:

fixes *u d*
defines *d* \equiv *degree u*
assumes *d*: $d \leq n$
and *lincomb*: *lincomb-list c (factorization-lattice u (n-d) k) = g (is ?l = ?r)*
shows *poly-mod.dvdm k u (poly-of-vec g)*
<proof>

lemma *dvd-modulo-to-lincomb*:

fixes *u :: int poly and d*
defines *d* \equiv *degree u*
assumes *d*: $d < n$
and *dvd*: *poly-mod.dvdm k u (poly-of-vec g)*
and *k-not0*: $k \neq 0$
and *monic-u*: *monic u*
and *dim-g*: *dim-vec g = n*
and *deg-u*: *degree u > 0*
shows $\exists c.$ *lincomb-list c (factorization-lattice u (n-d) k) = g*
<proof>

The factorization lattice precisely characterises the polynomials of a certain degree which divide *u* modulo *M*.

lemma *factorization-lattice*: **fixes** *M* **assumes**

deg-u: *degree u* $\neq 0$ **and** *M*: $M \neq 0$
shows $\text{degree } u \leq n \implies n \neq 0 \implies f \in \text{poly-of-vec 'lattice-of (factorization-lattice } u (n - \text{degree } u) M) \implies$
 $\text{degree } f < n \wedge \text{poly-mod.dvdm } M u f$
 $\text{monic } u \implies \text{degree } u < n \implies$
 $\text{degree } f < n \implies \text{poly-mod.dvdm } M u f \implies f \in \text{poly-of-vec 'lattice-of (factorization-lattice } u (n - \text{degree } u) M)$
<proof>
end

5.7 Soundness of the LLL factorization algorithm

lemma *LLL-short-polynomial*: **assumes** *deg-u-0*: *degree u* $\neq 0$ **and** *deg-le*: *degree*

u $\leq n$
and *pl1*: *pl* > 1
and *monic*: *monic u*
shows $\text{degree (LLL-short-polynomial } pl n u) < n$
and *LLL-short-polynomial pl n u* $\neq 0$
and *poly-mod.dvdm pl u (LLL-short-polynomial pl n u)*

and $\text{degree } u < n \implies f \neq 0 \implies$
 $\text{poly-mod.dvdm } pl \ u \ f \implies \text{degree } f < n \implies \|LLL\text{-short-polynomial } pl \ n \ u\|^2 \leq$
 $2^{\wedge}(n - 1) * \|f\|^2$
 <proof>

context *LLL-implementation*
begin

lemma *LLL-reconstruction*: **assumes** *LLL-reconstruction* $f \ us = fs$
and $\text{degree } f \neq 0$
and $\text{poly-mod.unique-factorization-m } pl \ f \ (\text{lead-coeff } f, \text{ mset } us)$
and $f \ \text{dvd } F$
and $\bigwedge ui. ui \in \text{set } us \implies \text{poly-mod.Mp } pl \ ui = ui$
and $F0: F \neq 0$
and $\text{cop: coprime } (\text{lead-coeff } F) \ p$
and $\text{sf: poly-mod.square-free-m } p \ F$
and $pl1: pl > 1$
and $plp: pl = p^{\wedge}l$
and $p: \text{prime } p$
and $\text{large: } 2^{\wedge}(5 * (\text{degree } F - 1) * (\text{degree } F - 1)) * \|F\|^2 \wedge (2 * (\text{degree } F - 1)) < pl^2$
shows $f = \text{prod-list } fs \wedge (\forall fi \in \text{set } fs. \text{irreducible}_d \ fi)$
 <proof>

lemma *LLL-many-reconstruction*: **assumes** *LLL-many-reconstruction* $f \ us = fs$
and $\text{degree } f \neq 0$
and $\text{poly-mod.unique-factorization-m } pl \ f \ (\text{lead-coeff } f, \text{ mset } us)$
and $f \ \text{dvd } F$
and $\bigwedge ui. ui \in \text{set } us \implies \text{poly-mod.Mp } pl \ ui = ui$
and $F0: F \neq 0$
and $\text{cop: coprime } (\text{lead-coeff } F) \ p$
and $\text{sf: poly-mod.square-free-m } p \ F$
and $pl1: pl > 1$
and $plp: pl = p^{\wedge}l$
and $p: \text{prime } p$
and $\text{large: } 2^{\wedge}(5 * (\text{degree } F \ \text{div } 2) * (\text{degree } F \ \text{div } 2)) * \|F\|^2 \wedge (2 * (\text{degree } F \ \text{div } 2)) < pl^2$
shows $f = \text{prod-list } fs \wedge (\forall fi \in \text{set } fs. \text{irreducible}_d \ fi)$
 <proof>

end

lemma *LLL-factorization*:
assumes $\text{res: LLL-factorization } f = gs$
and $\text{sff: square-free } f$
and $\text{deg: degree } f \neq 0$
shows $f = \text{prod-list } gs \wedge (\forall g \in \text{set } gs. \text{irreducible}_d \ g)$
 <proof>

lemma *LLL-many-factorization*:
assumes *res*: *LLL-many-factorization* $f = gs$
and *sff*: *square-free* f
and *deg*: *degree* $f \neq 0$
shows $f = \text{prod-list } gs \wedge (\forall g \in \text{set } gs. \text{irreducible}_d g)$
 $\langle \text{proof} \rangle$

lift-definition *one-lattice-LLL-factorization* :: *int-poly-factorization-algorithm*
is *LLL-factorization* $\langle \text{proof} \rangle$

lift-definition *many-lattice-LLL-factorization* :: *int-poly-factorization-algorithm*
is *LLL-many-factorization* $\langle \text{proof} \rangle$

lemma *LLL-factorization-primitive*:
assumes *LLL-factorization* $f = fs$ *square-free* f $0 < \text{degree } f$ *primitive* f
shows $f = \text{prod-list } fs \wedge (\forall fi \in \text{set } fs. \text{irreducible } fi \wedge 0 < \text{degree } fi \wedge \text{primitive } fi)$
 $\langle \text{proof} \rangle$

end

6 Calculating All Possible Sums of Sub-Multisets

theory *Sub-Sums*

imports

Main

HOL-Library.Multiset

begin

fun *sub-mset-sums* :: 'a :: *comm-monoid-add* *list* \Rightarrow 'a *set* **where**
sub-mset-sums [] = {0}
| *sub-mset-sums* (x # xs) = (let S = *sub-mset-sums* xs in S \cup ((+) x ' S)

lemma *subset-add-mset*: $ys \subseteq\# \text{add-mset } x \text{ } zs \iff (ys \subseteq\# zs \vee (\exists xs. xs \subseteq\# zs \wedge ys = \text{add-mset } x \text{ } xs))$
(is ?l = ?r)
 $\langle \text{proof} \rangle$

lemma *sub-mset-sums[simp]*: $\text{sub-mset-sums } xs = \text{sum-mset } \{ ys. ys \subseteq\# \text{mset } xs \}$
 $\langle \text{proof} \rangle$

end

7 Implementation and soundness of a modified version of Algorithm 16.22

Algorithm 16.22 is quite similar to the LLL factorization algorithm that was verified in the previous section. Its main difference is that it has an inner loop where each inner loop iteration has one invocation of the LLL basis reduction algorithm. Algorithm 16.22 of the textbook is therefore closer to the factorization algorithm as it is described by Lenstra, Lenstra, and Lovász [3], which also uses an inner loop.

The advantage of the inner loop is that it can find factors earlier, and then small lattices suffice where without the inner loop one invokes the basis reduction algorithm on a large lattice. The disadvantage of the inner loop is that if the input is irreducible, then one cannot find any factor early, so that all but the last iteration have been useless: only the last iteration will prove irreducibility.

We will describe the modifications w.r.t. the original Algorithm 16.22 of the textbook later in this theory.

theory *Factorization-Algorithm-16-22*

imports

LLL-Factorization

Sub-Sums

begin

7.1 Previous lemmas obtained using local type definitions

context *poly-mod-prime-type*

begin

lemma *irreducible-m-dvdm-prod-list-connect:*

assumes *irr: irreducible-m a*

and *dvd: a dvdm (prod-list xs)*

shows $\exists b \in \text{set } xs. a \text{ dvdm } b$

<proof>

end

lemma (**in** *poly-mod-prime*) *irreducible-m-dvdm-prod-list:*

assumes *irr: irreducible-m a*

and *dvd: a dvdm (prod-list xs)*

shows $\exists b \in \text{set } xs. a \text{ dvdm } b$

<proof>

7.2 The modified version of Algorithm 16.22

definition *B2-LLL* :: *int poly* \Rightarrow *int* **where**

B2-LLL $f = 2^{\wedge} (2 * \text{degree } f) * \|f\|^2$

```

hide-const (open) factors
hide-const (open) factors
hide-const (open) factor
hide-const (open) factor

```

```

context
  fixes  $p :: \text{int}$  and  $l :: \text{nat}$ 
begin

```

```

context
  fixes  $gs :: \text{int poly list}$ 
    and  $f :: \text{int poly}$ 
    and  $u :: \text{int poly}$ 
    and  $Degs :: \text{nat set}$ 
begin

```

This is the critical inner loop.

In the textbook there is a bug, namely that the filter is applied to g' and not to the primitive part of g' . (Problems occur if the content of g' is divisible by p .) We have fixed this problem in the obvious way.

However, there also is a second problem, namely it is only guaranteed that g' is divisible by u modulo p^l . However, for soundness we need to know that then also the primitive part of g' is divisible by u modulo p^l . This is not necessary true, e.g., if $g' = p^l$, then the primitive part is 1 which is not divisible by u modulo p^l . It is open, whether such a large g' can actually occur. Therefore, the current fix is to manually test whether the leading coefficient of g' is strictly smaller than p^l .

With these two modifications, Algorithm 16.22 will become sound as proven below.

```

definition LLL-reconstruction-inner  $j \equiv$ 
  let  $j' = j - 1$  in
  — optimization: check whether degree  $j'$  is possible
  if  $j' \notin Degs$  then None else
  — short vector computation
  let
     $ll = (\text{let } n = \text{sqrt-int-ceiling } (\|f\|^2 \wedge (2 * j') * 2 \wedge (5 * j' * j'));$ 
       $ll' = \text{find-exponent } p \ n \ \text{in } \text{if } ll' < l \ \text{then } ll' \ \text{else } l);$ 
    — optimization: dynamically adjust the modulus
     $pl = p \wedge ll;$ 
     $g' = \text{LLL-short-polynomial } pl \ j \ u$ 
  — fix: forbid multiples of  $p^l$  as short vector, unclear whether this is really required
  in if  $\text{abs } (\text{lead-coeff } g') \geq pl$  then None else
  let  $ppg = \text{primitive-part } g'$ 
  in
  — slight deviation from textbook: we check divisibility instead of norm-inequality
  case div-int-poly  $f \ ppg$  of Some  $f' \Rightarrow$ 

```

— fix: consider modular factors of ppg and not of g'
Some (filter ($\lambda gi. \neg \text{poly-mod.dvdm } p \text{ } gi \text{ } ppg$) gs, lead-coeff f', f', ppg)
 | *None* \Rightarrow *None*

function *LLL-reconstruction-inner-loop* **where**
LLL-reconstruction-inner-loop j =
 (if j > degree f then (\square , 1, 1, f)
 else case *LLL-reconstruction-inner* j
 of *Some* tuple \Rightarrow tuple
 | *None* \Rightarrow *LLL-reconstruction-inner-loop* (j+1))
 <proof>
termination <proof>

end

partial-function (*tailrec*) *LLL-reconstruction''* **where** [code]:
LLL-reconstruction'' gs b f factors =
 (if gs = \square then factors
 else
 let u = *choose-u* gs;
 d = degree u;
 gs' = *remove1* u gs;
 degs = map degree gs';
 Dega = ((+) d) ' *sub-mset-sums* degs;
 (gs', b', f', factor) = *LLL-reconstruction-inner-loop* gs f u Dega (d+1)
 in *LLL-reconstruction''* gs' b' f' (factor#factors)
)

definition *reconstruction-of-algorithm-16-22* gs f \equiv
 let G = \square ;
 b = lead-coeff f
 in *LLL-reconstruction''* gs b f G

end

definition *factorization-algorithm-16-22* :: int poly \Rightarrow int poly list **where**
factorization-algorithm-16-22 f = (let
 — find suitable prime
 p = *suitable-prime-bz* f;
 — compute finite field factorization
 (-, fs) = *finite-field-factorization-int* p f;
 — determine l and B
 n = degree f;
 — bound improved according to textbook, which uses $no = (n + 1) * (max - norm f)^2$
 no = $\|f\|^2$;
 — possible improvement: $B = \text{sqrt}(2^{5*n*(n-1)} * no^{2*n-1})$, cf. *LLL-factorization*

```

    B = sqrt-int-ceiling (2 ^ (5 * n * n) * no ^ (2 * n));
    l = find-exponent p B;
    — perform hensel lifting to lift factorization to mod pl
    vs = hensel-lifting p l f fs
    — reconstruct integer factors
    in reconstruction-of-algorithm-16-22 p l vs f)

```

7.3 Soundness proof

7.3.1 Starting the proof

Key lemma to show that forbidding values of p^l or larger suffices to find correct factors.

lemma (in *poly-mod-prime*) *Mp-smult-p-removal*: *poly-mod.Mp* ($p * p^k$) (*smult* $p f$) = 0 \implies *poly-mod.Mp* (p^k) $f = 0$
 ⟨*proof*⟩

lemma (in *poly-mod-prime*) *eq-m-smult-p-removal*: *poly-mod.eq-m* ($p * p^k$) (*smult* $p f$) (*smult* $p g$)
 \implies *poly-mod.eq-m* (p^k) $f g$ ⟨*proof*⟩

lemma *content-le-lead-coeff*: *abs* (*content* ($f :: \text{int poly}$)) \leq *abs* (*lead-coeff* f)
 ⟨*proof*⟩

lemma *poly-mod-dvd-drop-smult*: **assumes** u : *monic* u **and** p : *prime* p **and** c : $c \neq 0 \mid c < p^l$
and *dvd*: *poly-mod.dvdm* (p^l) u (*smult* $c f$)
shows *poly-mod.dvdm* $p u f$
 ⟨*proof*⟩

context

```

  fixes p :: int
    and F :: int poly
    and N :: nat
    and l :: nat
  defines [simp]: N  $\equiv$  degree F
  assumes p: prime p
    and N0: N > 0
    and bound-l: 2 ^ N2 * B2-LLL F ^ (2 * N)  $\leq$  (pl)2

```

begin

private lemma *F0*: $F \neq 0$ ⟨*proof*⟩ **lemma** *p1*: $p > 1$ ⟨*proof*⟩

interpretation p : *poly-mod-prime* p ⟨*proof*⟩

interpretation pl : *poly-mod* p^l ⟨*proof*⟩

lemma *B2-2*: $2 \leq B2\text{-LLL } F$
 ⟨*proof*⟩

lemma *l-gt-0*: $l > 0$
 ⟨*proof*⟩

lemma *l0*: $l \neq 0$ ⟨*proof*⟩

lemma *pl-not0*: $p \wedge l \neq 0$ ⟨*proof*⟩

interpretation *pl*: *poly-mod-2* $p \wedge l$
 ⟨*proof*⟩ **lemmas** *pl-dvdm-imp-p-dvdm* = *p.pl-dvdm-imp-p-dvdm*[*OF l0*]

lemma *p-Mp-pl-Mp[simp]*: $p.Mp (pl.Mp k) = p.Mp k$
 ⟨*proof*⟩

context
 fixes *u* :: *int poly*
 and *d* and *f* and *n*
 and *gs* :: *int poly list*
 and *Degs* :: *nat set*
 defines [*simp*]: $d \equiv \text{degree } u$
 assumes *d0*: $d > 0$
 and *u*: *monic u*
 and *irred-u*: *p.irreducible-m u*
 and *u-f*: *p.dvdm u f*
 and *f-dvd-F*: $f \text{ dvd } F$
 and [*simp*]: $n == \text{degree } f$
 and *f-gs*: *pl.unique-factorization-m f (lead-coeff f, mset gs)*
 and *cop*: *coprime (lead-coeff f) p*
 and *sf*: *p.square-free-m f*
 and *sf-F*: *square-free f*
 and *u-gs*: $u \in \text{set } gs$
 and *norm-gs*: $\text{map } pl.Mp \text{ } gs = gs$
 and *Degs*: $\bigwedge \text{factor. factor dvd } f \implies p.dvdm \text{ } u \text{ factor} \implies \text{degree factor} \in Degs$

begin
interpretation *pl*: *poly-mod-2* $p \wedge l$ ⟨*proof*⟩ **lemma** *f0*: $f \neq 0$ ⟨*proof*⟩ **lemma**
Mpf0: $pl.Mp f \neq 0$
 ⟨*proof*⟩ **lemma** *pMpf0*: $p.Mp f \neq 0$
 ⟨*proof*⟩ **lemma** *dn*: $d \leq n$ ⟨*proof*⟩ **lemma** *n0*: $n > 0$ ⟨*proof*⟩ **lemma** *B2-0[intro!]*:
B2-LLL $F > 0$ ⟨*proof*⟩ **lemma** *deg-u*: $\text{degree } u > 0$ ⟨*proof*⟩ **lemma** *n-le-N*: $n \leq N$
 ⟨*proof*⟩

lemma *dvdm-power*: **assumes** $g \text{ dvd } f$
shows $p.dvdm \text{ } u \text{ } g \iff pl.dvdm \text{ } u \text{ } g$
 ⟨*proof*⟩ **lemma** *uf*: $pl.dvdm \text{ } u \text{ } f$ ⟨*proof*⟩

lemma *exists-reconstruction*: $\exists h0. \text{irreducible}_d h0 \wedge p.dvdm \text{ } u \text{ } h0 \wedge h0 \text{ dvd } f$
 ⟨*proof*⟩

lemma *factor-dvd-f-0*: **assumes** *factor dvd f*
shows $pl.Mp \text{ factor} \neq 0$
 $\langle proof \rangle$

lemma *degree-factor-ge-degree-u*:
assumes *u-dvdm-factor: p.dvdm u factor*
and *factor-dvd: factor dvd f* **shows** $degree\ u \leq degree\ factor$
 $\langle proof \rangle$

7.3.2 Inner loop

context
fixes $j' :: nat$
assumes $dj': d \leq j'$
and $j'n: j' < n$
and $deg: \bigwedge factor. p.dvdm\ u\ factor \implies factor\ dvd\ f \implies degree\ factor \geq j'$
begin

private abbreviation (*input*) $j \equiv Suc\ j'$

private lemma *jn*: $j \leq n$ $\langle proof \rangle$ **lemma** *factor-irreducible_dI*: **assumes** $hf: h\ dvd\ f$
and $puh: p.dvdm\ u\ h$
and $degh: degree\ h > 0$
and $degh-j: degree\ h \leq j'$
shows *irreducible_d h*
 $\langle proof \rangle$ **definition** $ll = (let\ n = sqrt-int-ceiling\ (\|f\|^2 \wedge (2 * j') * 2 \wedge (5 * j' * j'));$
 $ll' = find-exponent\ p\ n\ in\ if\ ll' < l\ then\ ll' \ else\ l)$

lemma *ll*: $ll \leq l$ $\langle proof \rangle$

lemma *ll0*: $ll \neq 0$ $\langle proof \rangle$

lemma *pll1*: $p^{ll} > 1$ $\langle proof \rangle$

interpretation *pll*: *poly-mod-2* p^{ll}
 $\langle proof \rangle$

lemma *pll0*: $p^{ll} \neq 0$ $\langle proof \rangle$

lemma *dvdm-ll*: **assumes** $pl.dvdm\ a\ b$
shows $pll.dvdm\ a\ b$
 $\langle proof \rangle$ **definition** $g \equiv LLL-short-polynomial\ (p^{ll})\ j\ u$

lemma *deg-g-j*: *degree g < j*
and $g0: g \neq 0$
and $ug: pll.dvdm\ u\ g$
and $short-g: h \neq 0 \implies pll.dvdm\ u\ h \implies degree\ h \leq j' \implies \|g\|^2 \leq 2 \wedge j' *$

$\|h\|^2$
<proof>

lemma *LLL-reconstruction-inner-simps*: *LLL-reconstruction-inner* $p \ l \ gs \ f \ u \ Degr \ j$
= (if $j' \notin Degr$ then *None* else if $p \wedge ll \leq |lead-coeff \ g|$ then *None*
else case *div-int-poly* f (*primitive-part* g) of *None* \Rightarrow *None*
| *Some* $f' \Rightarrow$ *Some* ($[gi \leftarrow gs \ . \ \neg \ p.dvdm \ gi \ (\text{primitive-part } g)]$, *lead-coeff* f' ,
 f' , *primitive-part* g))
<proof>

lemma *LLL-reconstruction-inner-complete*:
assumes *ret*: *LLL-reconstruction-inner* $p \ l \ gs \ f \ u \ Degr \ j = \text{None}$
shows $\bigwedge \text{factor. } p.dvdm \ u \ \text{factor} \Rightarrow \text{factor} \ \text{dvd} \ f \Rightarrow \text{degree} \ \text{factor} \geq j$
<proof>

lemma *LLL-reconstruction-inner-sound*:
assumes *ret*: *LLL-reconstruction-inner* $p \ l \ gs \ f \ u \ Degr \ j = \text{Some} \ (gs', b', f', h)$
shows $f = f' * h$ (**is** ?g1)
and *irreducible_d* h (**is** ?g2)
and $b' = lead-coeff \ f'$ (**is** ?g3)
and *pl.unique-factorization-m* f' (*lead-coeff* f' , *mset* gs') (**is** ?g4)
and $p.dvdm \ u \ h$ (**is** ?g5)
and $degree \ h = j'$ (**is** ?g6)
and $length \ gs' < length \ gs$ (**is** ?g7)
and $set \ gs' \subseteq set \ gs$ (**is** ?g8)
and $gs' \neq []$ (**is** ?g9)
<proof>
end

interpretation *LLL* d <proof>

lemma *LLL-reconstruction-inner-None-upt-j'*:
assumes *ij*: $\forall i \in \{d+1..j\}. \text{LLL-reconstruction-inner } p \ l \ gs \ f \ u \ Degr \ i = \text{None}$
and *dj*: $d < j$ **and** $j \leq n$
shows $\bigwedge \text{factor. } p.dvdm \ u \ \text{factor} \Rightarrow \text{factor} \ \text{dvd} \ f \Rightarrow \text{degree} \ \text{factor} \geq j$
<proof>

corollary *LLL-reconstruction-inner-None-upt-j*:
assumes *ij*: $\forall i \in \{d+1..j\}. \text{LLL-reconstruction-inner } p \ l \ gs \ f \ u \ Degr \ i = \text{None}$
and *dj*: $d \leq j$ **and** *jn*: $j \leq n$
shows $\bigwedge \text{factor. } p.dvdm \ u \ \text{factor} \Rightarrow \text{factor} \ \text{dvd} \ f \Rightarrow \text{degree} \ \text{factor} \geq j$
<proof>

lemma *LLL-reconstruction-inner-all-None-imp-irreducible*:
assumes *i*: $\forall i \in \{d+1..n\}. \text{LLL-reconstruction-inner } p \ l \ gs \ f \ u \ Degr \ i = \text{None}$
shows *irreducible_d* f
<proof>

lemma *irreducible-imp-LLL-reconstruction-inner-all-None*:

assumes *irr-f*: *irreducible_a f*

shows $\forall i \in \{d+1..n\}$. *LLL-reconstruction-inner p l gs f u Degr i = None*
(*proof*)

lemma *LLL-reconstruction-inner-all-None*:

assumes *i*: $\forall i \in \{d+1..n\}$. *LLL-reconstruction-inner p l gs f u Degr i = None*

and *dj*: $d < j$

shows *LLL-reconstruction-inner-loop p l gs f u Degr j = ([], 1, 1, f)*
(*proof*)

corollary *irreducible-imp-LLL-reconstruction-inner-loop-f*:

assumes *irr-f*: *irreducible_a f* **and** *dj*: $d < j$

shows *LLL-reconstruction-inner-loop p l gs f u Degr j = ([], 1, 1, f)*
(*proof*)

lemma *exists-index-LLL-reconstruction-inner-Some*:

assumes *inner-loop*: *LLL-reconstruction-inner-loop p l gs f u Degr j = (gs', b', f', factor)*

and *i*: $\forall i \in \{d+1..<j\}$. *LLL-reconstruction-inner p l gs f u Degr i = None*

and *dj*: $d < j$ **and** *jn*: $j \leq n$ **and** *f*: $\neg \text{irreducible}_a f$

shows $\exists j'. j \leq j' \wedge j' \leq n \wedge d < j'$

\wedge (*LLL-reconstruction-inner p l gs f u Degr j' = Some (gs', b', f', factor)*)

\wedge ($\forall i \in \{d+1..<j'\}$. *LLL-reconstruction-inner p l gs f u Degr i = None*)

(*proof*)

lemma *unique-factorization-m-1*: *pl.unique-factorization-m 1 (1, {#})*

(*proof*)

lemma *LLL-reconstruction-inner-loop-j-le-n*:

assumes *ret*: *LLL-reconstruction-inner-loop p l gs f u Degr j = (gs', b', f', factor)*

and *ij*: $\forall i \in \{d+1..<j\}$. *LLL-reconstruction-inner p l gs f u Degr i = None*

and *n*: $n = \text{degree } f$

and *jn*: $j \leq n$

and *dj*: $d < j$

shows $f = f' * \text{factor}$ (**is** ?g1)

and *irreducible_a factor* (**is** ?g2)

and $b' = \text{lead-coeff } f'$ (**is** ?g3)

and *pl.unique-factorization-m f' (b', mset gs')* (**is** ?g4)

and *p.dvdm u factor* (**is** ?g5)

and $gs \neq [] \longrightarrow \text{length } gs' < \text{length } gs$ (**is** ?g6)

and *factor dvd f* (**is** ?g7)

and $f' \text{ dvd } f$ (**is** ?g8)

and $\text{set } gs' \subseteq \text{set } gs$ (**is** ?g9)

and $gs' = [] \longrightarrow f' = 1$ (**is** ?g10)

(*proof*)

lemma *LLL-reconstruction-inner-loop-j-ge-n*:

assumes *ret*: *LLL-reconstruction-inner-loop p l gs f u Degr j = (gs', b', f', factor)*

and $ij: \forall i \in \{d+1..n\}. \text{LLL-reconstruction-inner } p \text{ l } gs \text{ f } u \text{ Degr } i = \text{None}$
and $dj: d < j$
and $jn: j > n$
shows $f = f' * \text{factor}$ (**is** ?g1)
and $\text{irreducible}_d \text{ factor}$ (**is** ?g2)
and $b' = \text{lead-coeff } f'$ (**is** ?g3)
and $pl.\text{unique-factorization-m } f' (b', \text{mset } gs')$ (**is** ?g4)
and $p.\text{dvdm } u \text{ factor}$ (**is** ?g5)
and $gs \neq [] \longrightarrow \text{length } gs' < \text{length } gs$ (**is** ?g6)
and $\text{factor } dvd \text{ f}$ (**is** ?g7)
and $f' dvd \text{ f}$ (**is** ?g8)
and $\text{set } gs' \subseteq \text{set } gs$ (**is** ?g9)
and $f' = 1$ (**is** ?g10)
<proof>

lemma *LLL-reconstruction-inner-loop*:

assumes $ret: \text{LLL-reconstruction-inner-loop } p \text{ l } gs \text{ f } u \text{ Degr } j = (gs', b', f', \text{factor})$
and $ij: \forall i \in \{d+1..<j\}. \text{LLL-reconstruction-inner } p \text{ l } gs \text{ f } u \text{ Degr } i = \text{None}$
and $n: n = \text{degree } f$
and $dj: d < j$
shows $f = f' * \text{factor}$ (**is** ?g1)
and $\text{irreducible}_d \text{ factor}$ (**is** ?g2)
and $b' = \text{lead-coeff } f'$ (**is** ?g3)
and $pl.\text{unique-factorization-m } f' (b', \text{mset } gs')$ (**is** ?g4)
and $p.\text{dvdm } u \text{ factor}$ (**is** ?g5)
and $gs \neq [] \longrightarrow \text{length } gs' < \text{length } gs$ (**is** ?g6)
and $\text{factor } dvd \text{ f}$ (**is** ?g7)
and $f' dvd \text{ f}$ (**is** ?g8)
and $\text{set } gs' \subseteq \text{set } gs$ (**is** ?g9)
and $gs' = [] \longrightarrow f' = 1$ (**is** ?g10)
<proof>
end

7.3.3 Outer loop

lemma *LLL-reconstruction''*:

assumes $1: \text{LLL-reconstruction}'' p \text{ l } gs \text{ b } f \text{ G} = G'$
and $\text{irreducible-G}: \bigwedge \text{factor}. \text{factor} \in \text{set } G \implies \text{irreducible}_d \text{ factor}$
and $3: F = f * \text{prod-list } G$
and $4: pl.\text{unique-factorization-m } f (\text{lead-coeff } f, \text{mset } gs)$
and $5: gs \neq []$
and $6: \bigwedge gi. gi \in \text{set } gs \implies pl.Mp \text{ gi} = gi$
and $7: \bigwedge gi. gi \in \text{set } gs \implies p.\text{irreducible}_d\text{-m } gi$
and $8: p.\text{square-free-m } f$
and $9: \text{coprime } (\text{lead-coeff } f) \text{ p}$
and $sf\text{-}F: \text{square-free } F$
shows $(\forall g \in \text{set } G'. \text{irreducible}_d \text{ g}) \wedge F = \text{prod-list } G'$
<proof>

```

context
  fixes gs :: int poly list
  assumes gs-hen: berlekamp-hensel p l F = gs
  and cop: coprime (lead-coeff F) p
  and sf: poly-mod.square-free-m p F
  and sf-F: square-free F
begin

lemma gs-not-empty: gs ≠ []
  ⟨proof⟩

lemma reconstruction-of-algorithm-16-22:
  assumes 1: reconstruction-of-algorithm-16-22 p l gs F = G
  shows (∀ g ∈ set G. irreducibled g) ∧ F = prod-list G
  ⟨proof⟩
end
end

```

7.3.4 Final statement

```

lemma factorization-algorithm-16-22:
  assumes res: factorization-algorithm-16-22 f = G
  and sff: square-free f
  and deg: degree f > 0
  shows (∀ g ∈ set G. irreducibled g) ∧ f = prod-list G
  ⟨proof⟩

lift-definition increasing-lattices-LLL-factorization :: int-poly-factorization-algorithm
  is factorization-algorithm-16-22 ⟨proof⟩

thm factorize-int-poly[of increasing-lattices-LLL-factorization]

end

```

8 Mistakes in the textbook Modern Computer Algebra (2nd edition)

```

theory Modern-Computer-Algebra-Problem
  imports Factorization-Algorithm-16-22
begin

fun max-degree-poly :: int poly ⇒ int poly ⇒ int poly
  where max-degree-poly a b = (if degree a ≥ degree b then a else b)

fun choose-u :: int poly list ⇒ int poly
  where choose-u [] = undefined
  | choose-u [gi] = gi
  | choose-u (gi # gj # gs) = max-degree-poly gi (choose-u (gj # gs))

```

8.1 A real problem of Algorithm 16.22

Bogus example for Modern Computer Algebra (2nd edition), Algorithm 16.22, step 9: After having detected the factor $[1, 1, 0, 1]$, the remaining polynomial f^* will be 1, and the remaining list of modular factors will be empty.

lemma *let* $f = [1, 1] * [1, 1, 0, 1]$;
 $p = \text{suitable-prime-bz } f$;
 $b = \text{lead-coeff } f$;
 $A = \text{linf-norm-poly } f$; $n = \text{degree } f$; $B = \text{sqrt-int-ceiling } (n+1) * 2^n * A$;
 $Bnd = 2^{(n^2 \text{ div } 2)} * B^{(2*n)}$; $l = \text{log-ceiling } p \text{ } Bnd$;
 $(-, fs) = \text{finite-field-factorization-int } p \text{ } f$;
 $gs = \text{hensel-lifting } p \text{ } l \text{ } fs$;
 $u = \text{choose-u } gs$;
 $d = \text{degree } u$;
 $g\text{-star} = [2, 2, 0, 2 :: \text{int}]$;
 $(gs', hs') = \text{List.partition } (\lambda gi. \text{poly-mod.dvdm } p \text{ } gi \text{ } g\text{-star}) \text{ } gs$;
 $h\text{-star} = \text{smult } b \text{ } (\text{prod-list } hs')$;
 $f\text{-star} = \text{primitive-part } h\text{-star}$
in $(hs' = [] \wedge f\text{-star} = 1) \langle \text{proof} \rangle$

8.2 Another potential problem of Algorithm 16.22

Suppose that g^* is p^l . (It is not yet clear whether lattices exists where this g^* is short enough). Then $pp(g^*) = 1$ is detected as *irreducible* factor and the algorithm stops.

definition *input-poly* = $[1, 0, 0, 0, 1, 1, 0, 0, 1, 0, 1, 0, 1 :: \text{int}]$

For *input-poly* the factorization will result in a lattice where each initial basis element has a Euclidean norm of at least p^l (since the input polynomial u has a norm larger than p^l .) So, just from the norm of the basis one cannot infer that the lattice contains small vectors.

lemma *let* $f = \text{input-poly}$;
 $p = \text{suitable-prime-bz } f$;
 $b = \text{lead-coeff } f$;
 $A = \text{linf-norm-poly } f$; $n = \text{degree } f$; $B = \text{sqrt-int-ceiling } (n+1) * 2^n * A$;
 $Bnd = 2^{(n^2 \text{ div } 2)} * B^{(2*n)}$; $l = \text{log-ceiling } p \text{ } Bnd$;
 $(-, fs) = \text{finite-field-factorization-int } p \text{ } f$;
 $gs = \text{hensel-lifting } p \text{ } l \text{ } fs$;
 $u = \text{choose-u } gs$;
 $pl = p^l$;
 $pl2 = pl \text{ div } 2$;
 $u' = \text{poly-mod.inv-Mp2 } pl \text{ } pl2 \text{ } (\text{poly-mod.Mp } pl \text{ } (\text{smult } b \text{ } u))$
in $\text{sqrt-int-floor } (\text{sq-norm } u') > pl \langle \text{proof} \rangle$

The following calculation will show that the norm of g^* is not that much shorter than p^l which is an indication that it is not obvious that in general p^l cannot be chosen as short polynomial.

```

definition compute-norms = (let f = input-poly;
  p = suitable-prime-bz f;
  b = lead-coeff f;
  A = linf-norm-poly f; n = degree f; B = sqrt-int-ceiling (n+1) * 2^n * A;
  Bnd = 2^(n^2 div 2) * B^(2*n); l = log-ceiling p Bnd;
  (-, fs) = finite-field-factorization-int p f;
  gs = hensel-lifting p l f fs;
  u = choose-u gs;
  pl = p^l;
  pl2 = pl div 2;
  u' = poly-mod.inv-Mp2 pl pl2 (poly-mod.Mp pl (smult b u));
  d = degree u;
  pl = p^l;
  L = factorization-lattice u' 1 pl;
  g-star = short-vector 2 L
in (
  "p^l:          " @ show pl @ shows-nl [] @
  "norm u:      " @ show (sqrt-int-floor (sq-norm-poly u')) @ shows-nl [] @
  "norm g-star: " @ show (sqrt-int-floor (sq-norm-vec g-star)) @ shows-nl [] @
shows-nl []
))

```

export-code compute-norms in Haskell

- $p^l \approx 6.61056 \cdot 10^{122}$, namely 66105596879024859895191530803277103982840468296428121928464
- $norm\ u \approx 6.67555 \cdot 10^{122}$, namely 667555058938127908386141559707490406617756492853269306
- $norm\ g\text{-star} \approx 5.02568 \cdot 10^{110}$, namely 50256787188889378925810759939795033899734873138630

8.3 Verified wrong results

An equality in example 16.24 of the textbook which is not valid.

```

lemma let g2 = [-984,1:];
  g3 = [-72,1:];
  g4 = [-6828,1:];
  rhs = [-1728,-840,-420,6:];
in ¬ poly-mod.eq-m (5^6) (smult 6 (g2*g3*g4)) (rhs) <proof>

end

```

References

- [1] J. Divasón, S. J. C. Joosten, R. Thiemann, and A. Yamada. A formalization of the Berlekamp–Zassenhaus factorization algorithm. In *CPP 2017*, pages 17–29. ACM, 2017.

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