

Zeitschrift: L'Enseignement Mathématique
Herausgeber: Commission Internationale de l'Enseignement Mathématique
Band: 36 (1990)
Heft: 1-2: L'ENSEIGNEMENT MATHÉMATIQUE

Artikel: THE DISTANCE BETWEEN IDEALS IN THE ORDERS OF A REAL QUADRATIC FIELD
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Kapitel: 8. GAUSS'S REDUCTION PROCESS
DOI: <https://doi.org/10.5169/seals-57912>

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(ii) When $f = p$ (prime) and p does not divide a , we set $I_1 = I$. If p divides a , we take for I the ideal $a_1[1, \phi_1]$ following I in its period. In this case, as $p \mid a$, from $p^2 D = b_1^2 + 4aa_1$, we see that $p \mid b_1$ and so, as $\text{GCD}(a_1, b_1, a) = 1$ we see that p does not divide a_1 . Then, by (2.12), we have $I_1 = \rho I$ with $\rho = \frac{a_1}{a} \phi_1$. Now, by Proposition 5, $\phi_1 = \frac{b_1 + \sqrt{D'}}{2a_1}$ is reduced, so that $1 \leq b_1 < \sqrt{D'}$, and

$$(7.5) \quad 1 \leq a_1 < \sqrt{D'},$$

giving

$$(7.6) \quad 1 \leq \rho < \sqrt{D'}.$$

The rest of the proof follows exactly as in the proof of (i) using (7.5) (resp. (7.6)) in place of (7.3) (resp. (7.4)).

8. GAUSS'S REDUCTION PROCESS

Definition 14. (Half-reduced) A representation $\{a, b\}$ of an ideal I is said to be *half-reduced* if

$$(8.1) \quad 0 < \frac{-b + \sqrt{D}}{2|c|} < 1,$$

where $c = (D - b^2) \mid 4a$.

An ideal I is called *half-reduced* if there exists a half-reduced representation of I .

Clearly, if $\{a, b\}$ is half-reduced, then $b < \sqrt{D}$ and $\{-a, b\}$ is half-reduced.

LEMMA 7. Let I be a primitive ideal of O_D . To each representation $\{a, b\}$ of I corresponds a unique integer q such that the q -neighbour representation $\{a', b'\}$ is half-reduced. The integer b' and the ideal $I' = \left[a', \frac{b' + \sqrt{D}}{2} \right]$ are determined by I . The value of q is

$$(8.2) \quad q = \frac{a}{|a|} \left[\frac{b + \sqrt{D}}{2|a|} \right].$$

The representation $\{a', b'\}$ and the ideal I' are the Gauss neighbour of the representation $\{a, b\}$ and of the ideal I respectively, so that

$$\{a, b\} \xrightarrow{G} \{a', b'\}.$$

Proof. As $c' = \frac{(D - b'^2)}{4a'} = a$ (by (2.10)), the q -neighbour representation $\{a', b'\}$ of $\{a, b\}$ is half-reduced if

$$0 < \frac{-b' + \sqrt{D}}{2|a|} < 1,$$

that is, by (2.10), if $0 < \frac{b + \sqrt{D}}{2|a|} - \frac{a}{|a|} q < 1$, giving $q = \frac{a}{|a|} \left[\frac{b + \sqrt{D}}{2|a|} \right]$, which shows that q and $\{a', b'\}$ are determined by $\{a, b\}$. Let $\{\pm a, b + 2K|a|\} = \{a_1, b_1\}$ be another representation of I giving rise to a half-reduced representation, say $\{a'_1, b'_1\}$. As $b'_1 \equiv -b_1 \equiv -b \equiv b' \pmod{2|a|}$ and $|a_1| = |a|$, we see from the inequalities

$$0 < \frac{\sqrt{D} - b'}{2|a|} < 1 \quad \text{and} \quad 0 < \frac{\sqrt{D} - b'_1}{2|a_1|} < 1$$

that $b'_1 = b'$. Hence, as $|a| = |a_1|$ and $b' = b'_1$, from $D = b'^2 + 4aa' = b'^2_1 + 4a_1a'_1$, we see that $|a'| = |a'_1|$. This shows that $I'_1 = I$, which completes the proof of Lemma 7.

PROPOSITION 11. Let $\{a, b\}$ be a half-reduced representation of a half-reduced ideal I . Let $\{a, b\} \xrightarrow{G} \{a', b'\}$ and set $I' = \left[a', \frac{b' + \sqrt{D}}{2} \right]$. We have

- (i) if $b < -\sqrt{D}$ then $b' > b + 2\sqrt{D}$,
- (ii) if $b > -\sqrt{D}$ then I' is reduced.
- (iii) if I is reduced, then I' is reduced, and moreover if $\{a, b\}$ is the representation of I such that $a > 0$ and $\phi = \frac{b + \sqrt{D}}{2a}$ is reduced, then the Lagrange neighbour and the Gauss neighbour are the same.

Proof. For any representation $\{a, b\}$ of any primitive ideal, we have

$$(8.3) \quad \left| \frac{\sqrt{D} - b}{2c} \right| \left| \frac{\sqrt{D} + b}{2a} \right| = 1.$$

Now take $\{a, b\}$ to be a half-reduced representation of the half-reduced ideal I so that $0 < \frac{-b + \sqrt{D}}{2|c|} < 1$, where $c = (D - b^2)/4a$.

- (i) Suppose that $b < -\sqrt{D}$. Then we have $b^2 - D = 4|a||c|$ so that (8.3) becomes $\left(\frac{\sqrt{D}-b}{2|c|}\right)\left(\frac{-b-\sqrt{D}}{2|a|}\right) = 1$. As $0 < \frac{-b + \sqrt{D}}{2|c|} < 1$, we see that $\frac{-b - \sqrt{D}}{2|a|} > 1$. But, as $\{a', b'\}$ is also half-reduced, we have $\frac{-b' + \sqrt{D}}{2|a|} < 1$, so that $-b' + \sqrt{D} < 2|a| < -b - \sqrt{D}$, proving that $b' > b + 2\sqrt{D}$.
- (ii) Suppose that $b > -\sqrt{D}$. Then, we have $|b| < \sqrt{D}$, and (8.3) can be written

$$\left(\frac{\sqrt{D}-b}{2|c|}\right)\left(\frac{\sqrt{D}+b}{2|a|}\right) = 1.$$

showing that $\frac{\sqrt{D}+b}{2|a|} > 1$. On the other hand, as $\{a', b'\}$ is half-reduced, we have $0 < \frac{\sqrt{D}-b'}{2|a|} < 1$, that is $0 < \frac{\sqrt{D}+b}{2|a|} - \frac{a}{|a|}q < 1$, so that

$$\frac{a}{|a|}q = \left\lceil \frac{\sqrt{D}+b}{2|a|} \right\rceil \geq 1.$$

Hence we obtain

$$\sqrt{D} + b' = \sqrt{D} - b + 2aq = (\sqrt{D} - b) + 2|a|\left(\frac{aq}{|a|}\right) > 2|a|,$$

which, together with the inequalities $0 < \frac{\sqrt{D}-b'}{2|a|} < 1$, shows that ϕ' is

reduced if $a > 0$ and $-\phi'$ is reduced if $a < 0$, proving that I' is reduced.

- (iii) We suppose that I is reduced and choose the representation $\{a, b\}$ of I with $a > 0$ and $\phi = \frac{b + \sqrt{D}}{2a}$ reduced. As ϕ is half-reduced and $b > -\sqrt{D}$ from (ii)

we see that I' is reduced. Moreover, the integer q used to obtain both the Lagrange neighbour and the Gauss neighbour of $\{a, b\}$ is $[\phi]$. This shows that the two neighbours of $\{a, b\}$ are the same and concludes the proof of Proposition 11.

Definition 15. (Gauss's reduction process ([1]: §§ 183-185)) We start with

a primitive ideal I_0 of O_D and a representation $\{a, b\}$ of I_0 , and define the sequence of representations $\{a_n, b_n\}$ of the primitive ideals I_n by

$$\{a_n, b_n\} \xrightarrow{G} \{a_{n+1}, b_{n+1}\} \quad (n = 0, 1, 2, \dots).$$

We now show that Gauss's reduction process leads to a reduced ideal equivalent to I_0 . In addition we give an upper bound for the number of steps required to obtain a reduced ideal I_n as well as bounds for a quantity ρ in the relation $I_n = \rho I_0$.

PROPOSITION 12. (i) The ideal I_n is reduced for

$$n > \max \left(\left\lfloor \frac{|a_0|}{\sqrt{D}} \right\rfloor + 1, 2 \right).$$

(ii) Let I' be the first reduced ideal obtained by applying Gauss's reduction to I_0 . Then $I = \rho I_0$ with $\frac{1}{|a_0|} \leq \rho < \sqrt{D}$.

Proof. We suppose that $n > \max \left(\left\lfloor \frac{|a_0|}{\sqrt{D}} \right\rfloor + 1, 2 \right)$ so that $n \geq 3$.

If $b_1 > -\sqrt{D}$, by Proposition 11 (ii), I_2 is reduced and so, by Proposition 11 (iii), I_n is reduced.

Suppose on the other hand that $b_1 < -\sqrt{D}$ and that I_n is not reduced. Then, by Proposition 11 (ii), we see that $b_i < -\sqrt{D}$ for $i = 1, 2, \dots, n-1$. Then, by Proposition 11 (i), we have

$$b_{n-1} > b_1 + 2(n-2)\sqrt{D}.$$

Hence we obtain

$$\begin{aligned} b_{n-1} &> -b_0 + 2a_0 \left(\frac{a_0}{|a_0|} \left[\frac{a_0}{|a_0|} \frac{(b_0 + \sqrt{D})}{2a_0} \right] \right) + 2 \left(\frac{|a_0|}{\sqrt{D}} - 1 \right) \sqrt{D} \\ &> -b_0 + 2|a_0| \left(\frac{b_0 + \sqrt{D}}{2|a_0|} - 1 \right) + 2 \left(\frac{|a_0|}{\sqrt{D}} - 1 \right) \sqrt{D} \\ &= -\sqrt{D}, \end{aligned}$$

which is a contradiction. This completes the proof that I_n is reduced for $n > \max \left(\left\lfloor \frac{|a_0|}{\sqrt{D}} \right\rfloor + 1, 2 \right)$.

(ii) Let I_n be the first reduced ideal obtained from I_0 by Gauss's reduction

process. If $n = 0$ then $\rho = 1$, so that $\frac{1}{|a_0|} \leq \rho < \sqrt{D}$. If $n \geq 1$ we have $I_n = \rho I_0$ with (by (2.12))

$$\rho = \left| \frac{a_1}{a_0} \phi_1 \dots \frac{a_n}{a_{n-1}} \phi_n \right| = \left| \frac{a_n}{a_0} \right| \left| \frac{b_1 + \sqrt{D}}{2a_1} \right| \dots \left| \frac{b_n + \sqrt{D}}{2a_n} \right|.$$

As the representations $\{a_k, b_k\}$ are half-reduced for $k \geq 1$, we see, by (8.3), that $\left| \frac{b_k + \sqrt{D}}{2a_k} \right| > 1$ ($k \geq 1$) so that $\rho > \left| \frac{a_n}{a_0} \right| \geq \frac{1}{|a_0|}$. On the other hand we have

$$\rho = \left| \frac{b_1 + \sqrt{D}}{2a_0} \right| \dots \left| \frac{b_n + \sqrt{D}}{2a_{n-1}} \right|.$$

As $\{a_k, b_k\}$ is a half-reduced representation for $k = 1, 2, \dots, n$, we have $0 < \sqrt{D} - b_k < 2|a_{k-1}|$. Furthermore, for $k = 1, 2, \dots, n-1$, we have $\sqrt{D} + b_k < 2|a_{k-1}|$, as otherwise $0 < \sqrt{D} - b_k < 2|a_{k-1}| < \sqrt{D} + b_k$, which is equivalent to $0 < \sqrt{D} - b_k < 2|a_k| < \sqrt{D} + b_k$ so that by (4.2) the primitive ideal I_k would be reduced. Therefore, for $k = 1, 2, \dots, n-1$, we have

$$|\sqrt{D} + b_k| \leq \sqrt{D} + |b_k| = \begin{cases} \sqrt{D} + b_k < 2|a_{k-1}|, & \text{if } b_k \geq 0, \\ \sqrt{D} - b_k < 2|a_{k-1}|, & \text{if } b_k < 0, \end{cases}$$

so that, as $\{a_n, b_n\}$ is reduced,

$$\rho < \frac{b_n + \sqrt{D}}{2|a_{n-1}|} < \sqrt{D}$$

which completes the proof of Proposition 12.

We remark that Proposition 7 and 12 suggest that Lagrange's reduction process may lead to a reduced ideal much faster than Gauss's reduction process, as the number M_0 of Lemma 6 is much smaller than $\max \left(\frac{|a_0|}{\sqrt{D}} + 1, 2 \right)$.

Example 5. We apply both Lagrange reduction and Gauss reduction to the representation $\{3655, 7068\}$ of the primitive ideal $[3655, 3534 + \sqrt{21}]$ of O_{84} . We obtain

$$\{3655, 7068\} \xrightarrow{L} \{-3417, -7068\} \xrightarrow{L} \{4, 234\} \xrightarrow{L} \{3, 6\} \quad (3 \text{ steps})$$

and

$$\begin{aligned} \{3655, 7068\} \xrightarrow{G} \{-3417, -7068\} \xrightarrow{G} \{3187, -6600\} \xrightarrow{G} \{-2965, -6148\} \xrightarrow{G} \dots \\ \xrightarrow{G} \{-1, -12\} \xrightarrow{G} \{-5, 8\} \quad (30 \text{ steps}) . \end{aligned}$$

We remark that M_0 is approximately 8.72 and $\frac{|a_0|}{\sqrt{D}} + 1$ is approximately 399.8.

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