Notes on the proof of the theorem of Hasse–Arf

We reformulate the proof of the theorem of Hasse–Arf [1, Chap. V §7 Théorème 1], under the assumption that the residue field F of K is perfect and L is a totally ramified cyclic extension of K. In fact, the perfectness assumption is redundant but we omit the proof.

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Lemma 1. *Let K be a discrete valuation field and let L be a totally ramified cyclic extension of K of Galois group G. Define a subgroup A of $B = \mathcal{O}_L^\times$ by $A = \{s(u)/u \mid s \in G, u \in \mathcal{O}_L^\times\}$ and let $\mathrm{N}_{L/K}\colon B \to C = \mathcal{O}_K^\times$ denote the norm. Then, the morphism*

$$G \to H = \mathrm{Ker}(\mathrm{N}_{L/K}\colon B \to C)/A \tag{1}$$

sending s to $s(\pi)/\pi$ for a uniformizer π of L is an isomorphism independent of π.

Proof. Let $\sigma \in G$ be a generator and identify H with the Galois cohomology $\mathrm{H}^1(G, B) = \mathrm{Ker}(\mathrm{N}_{L/K}\colon \mathcal{O}_L^\times \to \mathcal{O}_K^\times)/(\sigma - 1)\mathcal{O}_L^\times$. Since L is totally ramified, the order of the cyclic group G equals the ramification index $e = e_{L/K}$. Since $\mathrm{H}^1(G, L^\times) = 0$ by Hilbert 90, the exact sequence $0 \to \mathcal{O}_L^\times \to L^\times \to \mathbf{Z} \to 0$ induces an isomorphism $\mathbf{Z}/e\mathbf{Z} \to H$ sending 1 to the class of $\sigma(\pi)/\pi$ independent of the choice of uniformizer π. Identifying $G = \langle\sigma\rangle$ with $\mathbf{Z}/e\mathbf{Z}$ by the generator σ, we obtain an isomorphism $G \to H$ sending σ^i to $(\sigma(\pi)/\pi)^i \equiv \sigma^i(\pi)/\pi$. □

We consider the filtration $B_m = 1 + \mathfrak{m}_L^m \subset B = \mathcal{O}_L^\times$ indexed by integers $m \geqq 1$ and the induced filtration $A_m = A \cap B_m$. For $m \geqq 1$, let $n \geqq 1$ be the largest integer such that $\mathrm{N}_{L/K}(B_m) \subset 1 + \mathfrak{m}_K^n$ and set $C_m = 1 + \mathfrak{m}_K^n$. For $X = A, B, C$, we also set $X_0 = X$ and define $\mathrm{Gr}_m X = X_m/X_{m+1}$ for $m \geqq 0$. We consider subcomplexes

$$A_m \to B_m \to C_m$$

of $A \to B \to C$ and the graded quotients

$$\mathrm{Gr}_m A \to \mathrm{Gr}_m B \to \mathrm{Gr}_m C.$$

The canonical morphism $\mathrm{Gr}_m A \to \mathrm{Gr}_m B$ is an injection. We define subgroups $H_m \subset H$ by $H_m = \mathrm{Ker}(\mathrm{N}\colon B_m \to C_m)/A_m$ and set $\mathrm{Gr}_m H = H_m/H_{m+1}$. We have $H_m = 0$ for m sufficiently large by [1, Chap. V §7 Lemme 9]).

Lemma 2. *Let $m \geqq 0$ be an integer.*

1. *The injection $H_m \to B_m/A_m$ induces an injection*

$$\mathrm{Gr}_m H \to \mathrm{Ker}(\mathrm{N}\colon \mathrm{Gr}_m B \to \mathrm{Gr}_m C)/\mathrm{Gr}_m A. \tag{2}$$

This is an isomorphism if K is complete and if the residue field F is algebraically closed.

2 ([1, Chap. V §6 Proposition 9]). *Assume that K is complete, that F is algebraically closed and that $\varphi(m)$ is an integer. Then, we have an isomorphism*

$$\mathrm{Gr}_m G \to \mathrm{Ker}(\mathrm{N}\colon \mathrm{Gr}_m B \to \mathrm{Gr}_m C). \tag{3}$$

Proof. 1. Since $H_m = \mathrm{Ker}(B_m/A_m \to C_m)$, by the commutative diagram

$$
(4)\qquad
\begin{array}{ccccccccc}
0 & \longrightarrow & B_{m+1}/A_{m+1} & \longrightarrow & B_m/A_m & \longrightarrow & \mathrm{Gr}_m B/\mathrm{Gr}_m A & \longrightarrow & 0 \\
 & & \downarrow & & \downarrow & & \downarrow & & \\
0 & \longrightarrow & C_{m+1} & \longrightarrow & C_m & \longrightarrow & \mathrm{Gr}_m C & \longrightarrow & 0
\end{array}
$$

of exact sequences, we obtain an injection $\mathrm{Gr}_m H \to \mathrm{Ker}(\mathrm{Gr}_m B/\mathrm{Gr}_m A \to \mathrm{Gr}_m C)$. If K is complete and F is algebraically closed, the vertical arrows in (4) are surjections by [1, Chap. V §6 Corollaire 4]. □

Proposition 3. *Let K be a discrete valuation field and L be a totally ramified cyclic extension of K. We consider the following conditions on integer $m \geqq 0$:*

(1) $\mathrm{Gr}_m H \neq 0$.

(2) *The injection* $\mathrm{Gr}_m A \to \mathrm{Gr}_m B$ *is not an isomorphism.*

(3) $\mathrm{Gr}_m A = 0$.

(4) $\mathrm{Gr}_m C \neq 0$.

(5) $\varphi(m)$ *is an integer.*

1. *Assume $m \geqq 1$. Then, we have* (1)⇒(2)⇔(3). *If K is complete and if the residue field F is algebraically closed, the conditions* (2), (3), (4) *and* (5) *are equivalent to each other.*

2. *Assume $m = 0$. Then, the conditions* (2), (3) *and* (4) *hold. If K is complete, then* (5) *also holds.*

Proof. 1. (1)⇒(2): The assertion follows from the injection $\mathrm{Gr}_m H \to \mathrm{Gr}_m B/\mathrm{Gr}_m A$ in Lemma 2.1.

(2)⇒(3) [1, Chap. V §7 Lemme 11]: We show the contraposition. Suppose $\sigma(1+x)/(1+x) \equiv 1 + (\sigma(x) - x) \in \mathrm{Gr}_m A$ is a non-trivial element for $x \in \mathfrak{m}_L$. Then, for $a \in \mathcal{O}_K$, we have $\sigma(1 + ax)/(1 + ax) \equiv 1 + a(\sigma(x) - x) \in \mathrm{Gr}_m B$ and $\mathrm{Gr}_m A \to \mathrm{Gr}_m B$ is a surjection.

(3)⇒(2): Since $\mathrm{Gr}_m B \neq 0$, the condition (3) implies (2).

(3)⇒(4): By the assumptions $\mathrm{Gr}_m A = 0$, that K is complete and that the residue field F is algebraically closed, we have an injection $\mathrm{Gr}_m B/\mathrm{Gr}_m H \to \mathrm{Gr}_m C$ by Lemma 2.1. Since $\mathrm{Gr}_m H$ is cyclic and $\mathrm{Gr}_m B$ is not, we have $\mathrm{Gr}_m C \neq 0$.

(4)⇒(5): Let $n \geqq 1$ be the integer such that $C_m = 1 + \mathfrak{m}_K^n$. By the definition of n, we have $1 + \mathfrak{m}_K^{n+1} \not\supset \mathrm{N}(1 + \mathfrak{m}_L^m) \subset 1 + \mathfrak{m}_K^n$. If $\mathrm{Gr}_m C \neq 0$, we have $\mathrm{N}(1 + \mathfrak{m}_L^{m+1}) \subset 1 + \mathfrak{m}_K^{n+1}$. For $m' = \psi(n)$, by the assumption that K is complete and F is algebraically closed, we have $\mathrm{N}(1 + \mathfrak{m}_L^{m'}) = 1 + \mathfrak{m}_K^n$ and $\mathrm{N}(1 + \mathfrak{m}_L^{m'+1}) = 1 + \mathfrak{m}_K^{n+1}$ by [1, Chap. V §6 Corollaire 3].

From $\mathrm{N}(1+\mathfrak{m}_L^{m'+1}) = 1+\mathfrak{m}_K^{n+1} \not\supset \mathrm{N}(1+\mathfrak{m}_L^m)$, we obtain $m'+1 > m$. From $\mathrm{N}(1+\mathfrak{m}_L^{m+1}) \subset 1+\mathfrak{m}_K^{n+1} \subsetneqq 1+\mathfrak{m}_K^n = \mathrm{N}(1+\mathfrak{m}_L^{m'})$, we obtain $m+1 > m'$ conversely. Thus, $m = m' = \psi(n)$ and $n = \varphi(m)$ is an integer.

(5)⇒(2): Assume that K is complete and the residue field F is algebraically closed. By Lemma 2.2, the condition (5) implies that the kernel $\mathrm{Ker}(\mathrm{N}\colon \mathrm{Gr}_m B \to \mathrm{Gr}_m C)$ is finite. Hence $\mathrm{Gr}_m A \subset \mathrm{Ker}(\mathrm{N}\colon \mathrm{Gr}_m B \to \mathrm{Gr}_m C)$ is also finite. Since $\mathrm{Gr}_m B$ is infinite, this implies (2).

2. Since G acts trivially on the residue field $E = F$ of L, we have $A_0 = A_0 \cap B_1 = A_1$ and (3) holds. As in 1, (3) implies (2) and the condition (2) also holds. We have $\mathrm{Gr}_0 C = \mathcal{O}_K^\times/1 + \mathfrak{m}_K^n \neq 0$ for some integer $n \geqq 1$ and (4) holds. Since $\varphi(0) = 0$, the condition (5) also holds. □

Corollary 4. *Assume that K is complete and that the residue field F is algebraically closed. Then, the morphism $G \to H$ (1) induces an isomorphism $\mathrm{Gr}_m G \to \mathrm{Gr}_m H$ for every $m \geqq 0$.*

Proof. We define an isomorphism assuming that $\mathrm{Gr}_m H \neq 0$. By Lemma 2.1, we have an isomorphism $\mathrm{Gr}_m H \to \mathrm{Ker}(\mathrm{N}\colon \mathrm{Gr}_m B/\mathrm{Gr}_m A \to \mathrm{Gr}_m C)$ (2). By Proposition 3 (1)⇒(5) and Lemma 2.2, we have an isomorphism $\mathrm{Gr}_m G \to \mathrm{Ker}(\mathrm{N}\colon \mathrm{Gr}_m B \to \mathrm{Gr}_m C)$ (3). By Proposition 3 (1)⇒(3), we have $\mathrm{Gr}_m A = 0$ and we obtain an isomorphism $\mathrm{Gr}_m G \to \mathrm{Gr}_m H$. The isomorphism is induced by $G \to H$ (1).

By the isomorphisms, we have either $\#\mathrm{Gr}_m H = \#\mathrm{Gr}_m G$ or $\mathrm{Gr}_m H = 0$ for each $m \geqq 0$. Hence, we obtain $\#H = \prod_{m\geqq 0} \#\mathrm{Gr}_m H \leqq \prod_{m \geqq 0} \#\mathrm{Gr}_m G = \#G$ and the equality is equivalent to $\#\mathrm{Gr}_m H = \#\mathrm{Gr}_m G$ for every $m \geqq 0$. Since the equality holds by Lemma 1, we have $\#\mathrm{Gr}_m H = \#\mathrm{Gr}_m G$ for every $m \geqq 0$. □

Theorem 5. *Let K be a complete discrete valuation field and L be a totally ramified cyclic extension of K. If $\mathrm{Gr}_m G \neq 0$, then $\varphi(m)$ is an integer.*

Proof. By replacing K by the completion $\widehat{K}_{\mathrm{ur}}$ of a maximal unramified extension and L by the composition field $\widehat{L}_{\mathrm{ur}} = L\widehat{K}_{\mathrm{ur}}$, we may assume that F is algebraically closed. Then the assertion follows from Corollary 4 and Proposition 3 (1)⇒(5). □

References

[1] Jean-Pierre Serre, Corps locaux, Hermann, Paris.