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## 5. REMARKS ON COROLLARY 2

Corollary 2 does not remain true if we delete (b). In fact, take e.g.  $L = \mathbf{Q}(t, \sqrt{2(t^2 - 5)})$ ,  $f(t) = 5$  and let  $p > 5$ . Then 2 is a norm from  $\mathbf{Q}_p(\sqrt{5})$  to  $\mathbf{Q}_p$ , so  $2(t^2 - 5)$  is a norm from  $\mathbf{Q}_p(t, \sqrt{5})$  to  $\mathbf{Q}_p(t)$ , namely we can write

$$a_p(t)^2 - 5b_p(t)^2 = 2(t^2 - 5)$$

for suitable  $a_p, b_p \in \mathbf{Q}_p(t)$ . Necessarily  $b_p$  is nonzero, so 5 is a norm from  $\mathbf{Q}_p L$  to  $\mathbf{Q}_p(t)$  for all  $p > 5$ . On the other hand simple congruence considerations show that this is not true for  $p = 5$ .

An assumption which may perhaps seem more natural than (a), is that (for  $v = p$ )  $f$  is a norm from  $\widehat{\mathbf{Q}_p L}$  to  $\widehat{\mathbf{Q}_p(t)}$ , where the *hat* denotes completion with respect to an extension of the Gauss norm on  $\mathbf{Q}_p(t)$ . This last assumption is directly related to the solvability of a congruence  $N(t, x_1, \dots, x_d) \equiv f \pmod{p}$  with  $x_i \in \mathbf{F}_p(t)$ . When such a congruence is solvable, Hensel's principle may lead to a solution with  $x_i \in \widehat{\mathbf{Q}_p(t)}$ , but not perhaps with  $x_i \in \mathbf{Q}_p(t)$ .

However *a posteriori* the solvability of the above congruence is equivalent with any of the mentioned assumptions, for almost all  $p$ . We sketch a proofs of this claim.

Take first  $p$  to be a prime not dividing  $d$  and such that the cover  $L/K$  has good reduction at  $p$ . By this we mean that the Gauss norm on  $\mathbf{Q}_p(t)$  admits only one extension to  $\mathbf{Q}_p L$ . Denote by  $L(p)$  the residue field of  $L$  with respect to this extended valuation. Then  $L(p)$  is cyclic of degree  $d$  over  $\mathbf{F}_p(t)$ . Also, it goes back to Deuring that the genus of  $L(p)$  does not exceed the genus of  $L$ . We remark that it is well known that these properties are satisfied by all but finitely many  $p$ . For large  $p$  we may also suppose that the reductions of the  $\omega_i$ 's are linearly independent over  $\mathbf{F}_p(t)$ . In that case to say that  $f$  is a norm from  $L(p)$  is equivalent to solving (13) with  $x_i \in \mathbf{F}_p[t]$ .

We now define certain relevant projective varieties. Consider the equation

$$(13) \quad N(t, x_1, \dots, x_d) = x_0^d f,$$

where the  $x_i$ 's are polynomials of degree  $\leq B$ . This is equivalent to a certain system of homogeneous equations over  $\mathbf{Q}$  (each of degree  $d$ ) in the coefficients of the  $x_i$ 's. Such a system defines a variety in  $\mathbf{P}^{(d+1)(B+1)-1}$  which we denote by  $V_B$ . To find a point of  $V_B$  over a field  $k$  means to find a nontrivial solution of (13) with  $x_i \in k[t]$  of degree  $\leq B$ . In particular we may then represent  $f$  as a norm from  $kL$ .

We pause to note a fact not without interest in itself. Let  $\mathbf{k}$  be any field and let  $\mathbf{L}$  be a cyclic,  $\mathbf{k}$ -regular separable extension of  $\mathbf{k}(t)$  with Galois group  $\Gamma$  of order  $d$ . Let  $g$  be the genus of  $\mathbf{L}$ . By  $\deg_{\mathbf{L}}$  we shall mean the degree (of a function or divisor) referred to  $\mathbf{L}$ , while  $\deg$  will be referred to  $\mathbf{k}(t)$ . We have

PROPOSITION. *If  $f$  is a norm from  $\mathbf{L}$  to  $\mathbf{k}(t)$ , then it is the norm of a function  $\psi \in \mathbf{L}$  with  $\deg_{\mathbf{L}} \psi \leq \deg f + g + d - 1$ .*

To prove this assertion, let  $N = N_{\mathbf{k}(t)}^{\mathbf{L}}$  be the mentioned norm and write  $f = N(\phi)$ . Let  $F$  be a prime divisor of  $\mathbf{k}(t)$  appearing in  $f$  with multiplicity  $m = m_F$ . We may write, as in the proof of Corollary 2,

$$F = e(G_1 + \cdots + G_r).$$

where the  $G_i$  are prime divisors of  $\mathbf{L}$ , rational over  $\mathbf{k}$ ,  $e = e_F$  is the ramification index and  $G_i = \gamma^{i-1}(G_1)$ . We have  $\deg_{\mathbf{L}} F = d \deg F = er \deg_{\mathbf{L}} G_1$ . By taking norms we have  $dF = er \sum_{\sigma \in \Gamma} \sigma(G_1)$ . Let  $\sum m_i G_i$  be the part of  $\text{div}(\phi)$  made up with the  $G_i$ 's. Since  $N(\phi) = f$  we have  $d(\sum m_i) = erm$ . Hence  $|\sum m_i| \leq |erm/d|$  and we may write  $\sum m_i G_i = m' G_1 + \sum m'_i G_i$ , where  $|m'| \leq |erm/d|$  and  $\sum m'_i = 0$ . Also,  $\sum m'_i G_i$  can be written as a sum of terms  $G_i - G_j$ ,  $i < j$ . In turn,  $G_i - G_j = \sum_{s=i}^{j-1} (G_s - G_{s+1})$  is of the form  $G - \gamma(G)$  for some rational divisor  $G$ . These arguments prove that we may write the divisor of  $\phi$  in the form  $D_+ - D_- + (D - \gamma(D))$ , where  $D_+, D_-, D$  are  $\mathbf{k}$ -rational,  $D_+, D_-$  are positive and

$$\deg_{\mathbf{L}} D_{\pm} \leq \sum_{\pm m_F \geq 0} (\pm m_F) \frac{er}{d} \deg_{\mathbf{L}} G_1 \leq \sum_{\pm m_F \geq 0} m_F \deg F = \deg f.$$

Take now the divisor  $Z$  of zeros of the function  $t$ , say. This is positive of  $\mathbf{L}$ -degree  $d$ , rational over  $\mathbf{k}$  and invariant by  $\Gamma$ . Let  $h$  be the least integer such that  $\deg D + hd \geq g$ . Then  $g \leq \deg(D + hZ) \leq g + d - 1$ . By Riemann-Roch there exists a function  $\xi \in \mathbf{L}$  such that its divisor is of the form  $E - D - hZ$ , where  $E$  is positive. Since  $D, Z$  and  $\xi$  are rational over  $\mathbf{k}$ ,  $E$  is also rational over  $\mathbf{k}$ . Also,  $\deg_{\mathbf{L}} E = \deg_{\mathbf{L}} D + hd \leq g + d - 1$ . Put  $\psi = \phi \frac{\xi}{\gamma(\xi)}$ . Then

$$\begin{aligned} \text{div}(\psi) &= D_+ - D_- + D - \gamma(D) + E - D - hZ - \gamma(E) + \gamma(D) + hZ \\ &= D_+ - D_- + E - \gamma(E). \end{aligned}$$

Therefore the divisor of zeros of  $\psi$  has degree (in  $\mathbf{L}$ ) bounded by  $\deg_{\mathbf{L}}(E + D_+) \leq \deg f + g + d - 1$ . Also  $N(\psi) = N(\phi) = f$ . This proves the claim.

COROLLARY. *If  $f$  is a norm from  $kL$  to  $k(t)$ , then  $V_B$  has a  $k$ -point for some  $B$  bounded only in terms of  $\deg f$  and  $L$  (but not on  $k$ ).*

Here  $k$  is any field of characteristic zero and  $kL := k(t) \otimes_{Q(t)} L$ . To prove the assertion, let  $\psi$  be as in the Proposition (with  $\mathbf{L} = kL$ ,  $\mathbf{k} = k$ ) and write  $\psi = \sum_{i=1}^d y_i \omega_i$  with  $y_i \in k(t)$ . Conjugating the equation over  $k(t)$  we obtain a  $d \times d$  invertible linear system in the  $y_i$ 's, namely  $\sigma(\psi) = \sum_{i=1}^d y_i \sigma(\omega_i)$  for  $\sigma \in \Gamma$ . We may solve this system for the  $y_i$  and express them as linear combinations of the  $\sigma(\psi)$  with coefficients depending only on the basis  $\{\omega_i\}$ . On the other hand the  $(kL)$ -degree of  $\sigma(\psi)$  is bounded as in the Proposition. Since the degree is subadditive and  $\deg y_i = (\deg_{kL} y_i)/d$ , we see that  $\deg y_i$  is bounded depending only on  $\deg f$  and  $L$ . Therefore we may write  $y_i = x_i/x_0$ , where the  $x_i$ 's are polynomials in  $k[t]$  whose degree is likewise bounded, say by  $B = B(\deg f, L)$ , and the claim follows.

Applying then the Proposition with  $\mathbf{L} = L(p)$ ,  $\mathbf{k} = \mathbf{F}_p$  and arguing as in the above Corollary we may assume that the degrees of the  $x_i$ 's are bounded in terms of  $\deg f$  and  $L$  only. In turn, this is like finding an  $\mathbf{F}_p$ -point on the reduction of  $V_B$ , provided  $B = B(\deg f, L)$  is large enough.

Now we observe the following fact: *Given a projective variety  $V/\mathbf{Q}$ , for almost all  $p$  the existence of a point over  $\mathbf{F}_p$  in the reduction of  $V \bmod p$  is equivalent to the existence of a point in  $V(\mathbf{Q}_p)$ .*

(We tacitly assume to choose a set of defining equations for  $V$  and to define the reduction of  $V$  by reducing modulo  $p$  the equations, for large  $p$ .) This claim is most probably well known, but we have no reference. We just sketch a proof of the nontrivial part by induction on  $\dim V$ . If  $V$  is a finite set of points and some such point  $P$  reduces in  $\mathbf{F}_p$  modulo some prime ideal above  $p$ , then  $\mathbf{Q}(P)$  may be embedded in  $\mathbf{Q}_p$  for large  $p$ . Suppose  $m = \dim V \geq 1$ . We may assume that  $V$  is  $\mathbf{Q}$ -irreducible and express it as a union of absolutely irreducible varieties  $W_\sigma$  defined over a number field  $k$  and conjugate over  $\mathbf{Q}$ . Suppose  $V$  has a point over  $\mathbf{F}_p$ , where  $p$  is large. Then there exist some  $W_\sigma$  and a prime  $\pi$  of  $k$ , lying above  $p$ , such that the reduction of  $W_\sigma$  modulo  $\pi$  has a point over  $\mathbf{F}_p$ . If such a reduction is defined over  $\mathbf{F}_p$  then it contains points over  $\mathbf{F}_p$  in any prescribed Zariski open subset; in fact the reduction is absolutely irreducible for large  $p$  and we may apply the Lang-Weil theorem [Se2, Thm. 3.6.1, p.30]. In this case Hensel's principle gives a point of  $W_\sigma$  over  $\mathbf{Q}_p$ . If the reduction is not defined over  $\mathbf{F}_p$ , then the mentioned point lies in the intersection with some other conjugate over  $\mathbf{F}_p$ , i.e. in the reduction of

some intersection  $W_\sigma \cap W_\tau$  of distinct conjugates. This has smaller dimension and induction applies.

In conclusion, for large  $p$  and  $B$  as above we have that the following are equivalent: (i)  $f$  is norm from  $\mathbf{Q}_p L$ ; (ii)  $V_B$  has a  $\mathbf{Q}_p$ -point; (iii)  $V_B$  has an  $\mathbf{F}_p$ -point; (iv)  $f$  is a norm from  $L(p)$ .

We finally observe that the varieties  $V_B$  so defined satisfy the usual local-global principle, in view of the above Corollary 2 (with  $\Sigma = \emptyset$ ) and in view of the Corollary to the Proposition (applied with  $\mathbf{k} = \mathbf{Q}$  and  $\mathbf{k} = \mathbf{Q}_v$ ).

REMARK 2. A proof of the equivalence of (i) and (iv) may also be given by arguments partially analogous to the proof of the Theorem, without invoking the Proposition or the varieties  $V_B$ . We start by finding a solution over a finite normal extension  $k$  of  $\mathbf{Q}$ . We embed  $k$  in a finite extension  $k_v$  of  $\mathbf{Q}_p$  and we consider the functions  $\psi_\sigma$ ,  $L_\sigma$ ,  $Q_{\sigma,\tau}$  for  $\sigma, \tau \in G' := \text{Gal}(k_v/\mathbf{Q}_p)$ ; for large  $p$  we may reduce everything modulo  $v$ , denoting it with a tilde, finding a similar situation over the residue field  $\mathbf{F}_v$  of  $k_v$ . Also, we may assume that  $\text{Gal}(\mathbf{F}_v/\mathbf{F}_p) \cong G'$ . By assumption, there exists  $\xi \in L(p)$  with norm  $\tilde{f}$ . Then  $\tilde{\varphi}$  and  $\xi$  have the same norm, whence  $\tilde{\varphi} = \xi(A/\gamma A)$  for some  $A \in \mathbf{F}_v L(p)$ . This easily leads to  $\tilde{L}_\sigma = (A/\sigma A)\tilde{B}_\sigma(t)$ , where  $\tilde{B}_\sigma \in \mathbf{F}_v(t)$ . In turn we find that  $\tilde{Q}_{\sigma,\tau} = \partial(\tilde{B}_\sigma)$ . If  $p$  is so large that no two zeros or poles of  $Q_{\sigma,\tau}$  may collapse after reduction, then it is easily seen that we may find rational functions  $B_\sigma \in k_v(t)$  such that  $Q_{\sigma,\tau}/\partial(B_\sigma) \in k_v$ , reducing to the case when the  $Q_{\sigma,\tau}$  are constant. Actually, by using equations (5), we reduce to the case when they are roots of unity in  $k_v$ , in which case the proof is easily completed.

## 6. EFFECTIVENESS

The problem is the following. How can we decide whether a given  $f$  admits a nontrivial representation in the form (13), with  $x_i \in \mathbf{Q}[t]$ ? An answer can be given with the methods at the end of the last section. In fact, we have proved that if some representation exists, then a certain projective variety  $V$  (whose equations can be found) has a  $\mathbf{Q}$ -point and conversely. We have observed that  $V$  satisfies the local-global principle. Known methods allow one to decide whether  $V$  has points over all  $\mathbf{Q}_v$  and this gives an answer to the original question.